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Patterns of F2-layer variability

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Abstract

The ionosphere displays variations on a wide range of time-scales, ranging from operational time-scales of hours and days up to solar cycles and longer. We use ionosonde data from thirteen stations to study the day-to-day variability of the peak F2-layer electron density, $NmF2$, which we use to define quantitative descriptions of variability versus local time, season and solar cycle. On average, for years of medium solar activity (solar decimetric flux approximately 140 units), the daily fluctuations of $NmF2$ have a standard deviation of 20% by day and 33% by night. We examine and discuss the patterns of behaviour of ionospheric and geomagnetic variability, in particular the equinoctial peaks. For further analysis we concentrate on one typical midlatitude station, Slough. We find that the standard deviations of day-to-day and night-to-night values of Slough $NmF2$ at first increase with increasing length of the dataset, become fairly constant at lengths of 10–20 days and then increase further (especially at equinox) because of seasonal changes. We found some evidence of two-day waves, but they do not appear to be a major feature of Slough's F2 layer. Putting together the geomagnetic and ionospheric data, and taking account of the day-to-day variability of solar and geomagnetic parameters, we find that a large part of F2-layer variability is linked to that of geomagnetic activity, and attribute the rest to 'meteorological' sources at lower levels in the atmosphere. We suggest that the greater variability at night is due to enhanced auroral energy input, and to the lack of the strong photochemical control of the F2-layer that exists by day. © 2001 Elsevier Science Ltd. All rights reserved.

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1. Ionospheric variability and its causes

1.1. Background

The ionosphere plays a unique role in the Earth's environment because of strong coupling processes to regions below and above. Its interface at low altitudes is to a dense neutral atmosphere, itself modulated by tropospheric weather and surface topology. At high altitudes, space plasma processes in the magnetosphere, instigated by its coupling to the solar wind and interplanetary magnetic field (IMF), provide an interface with highly variable inputs of energetic particles and electrodynamic energy. As such, ionospheric variations form a significant aspect of the complex subject of space weather, which is pursued for its practical applications as well as for its scientific interest. The time-scales range from long-term (secular) changes down to operational time-scales of days, hours and even minutes.

The photochemical processes that govern the production and decay of the ionospheric plasma are reasonably well understood (Rishbeth and Garriott, 1969; Banks and Kockarts, 1973), and so are the roles of thermodynamic and electrodynamic processes, at least in the undisturbed F-layer. This is largely due to the development of theoretical models of the thermosphere–ionosphere system that successfully match many observed features of the peak electron density $NmF2$ and other F-layer properties. From simple models that included production, recombination and diffusion, there followed models of the F2-layer effects of

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thermospheric winds (e.g., Kohl et al., 1968) and electric fields (Moffett, 1979). The newer global thermosphere–ionosphere coupled models have been applied to studies of aeronomy (Roble et al., 1988), electrodynamics (Richmond et al., 1992), magnetic storms (e.g., Fuller-Rowell et al., 1994, 1996) and seasonal variations (Millward et al., 1996; Zou et al., 2000). Quite good convergence was found between the mean ionospheric behaviour or 'climatology' given by different models (Anderson et al., 1998) at a single midlatitude site, Millstone Hill. Model validation continues to be an active area in ionospheric research, with more emphasis now placed on studies of individual periods as opposed to global climatology. As a prelude to further theoretical studies of ionospheric variability, the present paper deals with the day-to-day variations of the ionosphere, a domain that includes geomagnetic storm effects as an important source of variability. This topic was pursued actively in the 1970s (as summarized below), but was then dormant except for studies of IMF effects (D'Angelo, 1980; Mendillo and Schatten, 1983; Bremer, 1988, 1996). Recently, there has been renewed interest in the subject, with studies such as the statistical analysis by Forbes et al. (2000) and the modelling of the ionospheric response to geomagnetic activity by Fuller-Rowell et al. (2000).

1.2. Prior studies

In addition to the mean or 'climatological' behaviour of the ionosphere, there is a persistent day-to-day variability or 'weather'. Given that different ionospheric layers are dominated by specific processes, the uncertainty at any given altitude may arise from poor knowledge of its mean behaviour or of its variability about a known mean. That is, the dominance of 'climate' versus 'weather' is itself an ionospheric variable. Many studies of these effects were carried out in the so-called 'applications' literature that pre-dated the current 'space weather' studies by several decades. These studies were often reported at technical meetings or in contract reports, but were not always published in standard research journals for ionospheric physics. For example, Rush and Gibbs (1973) reviewed the status of short-term predictions of radio propagation conditions at midlatitudes by examining the hourly critical frequencies foE, $foF1$, and $foF2$ of the E,F1 and F2 layers. For the E-layer during 0900–1500 local time (LT), the observed standard deviations for foE are generally less than 6% of the monthly mean, implying that 95% of all observations lie within $\pm 12\%$ of their median value. For $foF1$, the percentage deviations are only slightly greater, being greatest in solar maximum years. The conclusion reached was that for most needs the day-to-day variability of foE and $foF1$ is such that monthly mean or median values can be used to represent the diurnal variation. This implies that forecasters' attention should be given to the methods of predicting average behaviour, rather than to ways of taking into account the inherent variability of the E and F1 layers. This has been a fruitful avenue in that the median values of foE and $foF1$ at midlatitudes can mostly be predicted to within an accuracy of $\pm 5\%$ (Muggleton, 1972; DuCharme et al., 1971).

For the F2-layer, the situation is quite the opposite. Drawing upon a comprehensive study by Rush (1976), it is generally thought that the standard deviation of monthly mean $foF2$ at midlatitudes is about $\pm 15\%$ (corresponding to 25–30% for $NmF2$) at all seasons and solar cycle conditions. Mendillo et al. (1972) and Johanson et al. (1978) showed that the same is true of the ionosphere's total electron content (TEC), indicating that simple redistributions of the electron density versus height profile, $N(h)$, are not major causes of variability at the height ($hmF2$) of the peak F2-layer electron density. With the worldwide network of global positioning system (GPS) receivers being a key resource for space weather specification, forecasting and model validation, understanding the components of F-layer variability assumes a new relevance to basic environmental science.

It has long been recognized that geomagnetic activity is a dominant cause of ionospheric variability. For example, Mendillo and Schatten (1983), who studied the effect of magnetic activity on ionospheric total electron content (TEC), showed that variations from monthly means show a remarkably consistent anticorrelation between magnetically quiet versus disturbed days. The asymmetries they noted between the five quietest days (QQ) and the five most disturbed days (DD) are most pronounced at night. This is a purely statistical effect in the sense that small changes in F2-layer electron density result in large percentage changes when reckoned with respect to low nighttime mean values. The daytime variability, while small on a percentage basis, involves larger absolute changes in plasma content, and are therefore more significant, both physically and for applications. For example, HF propagation frequencies used for communications or GPS group delay corrections needed for navigation are always more variable in absolute units during the daytime. Similarly, the adjustments to winds, composition or electrodynamics in global models required to reproduce observations are of larger magnitude by day, as shown for example by Pi et al. (1993).

1.3. The present work

A recent paper by Forbes et al. (2000) discusses in detail the variability of $NmF2$ at 'high frequencies' (periods of < 1–2 days) and 'low frequencies' (periods of 2–30 days), how it varies with latitude, and the relative importance of solar photon flux, solar wind/geomagnetic activity, and 'meteorological' effects transmitted from lower levels in the atmosphere. It studies the contributions of the solar cycle, annual and semiannual variations but does not separate the data by day or night or by season. The present paper, too, concentrates on the day-to-day variability of $NmF2$ which, though less spectacular than the effects of well-defined

Table 1
Possible causes of ionospheric F-layer variability

1. *Solar ionizing radiation*	3. *Neutral atmosphere*
Solar flares	Solar and lunar tides: generated within thermosphere or coupled through mesosphere
Solar rotation (27 day) variations	Acoustic and gravity waves
Formation and decay of active regions	Planetary waves and 2-day oscillations
Seasonal variation of Sun's declination	Quasi-biennial oscillation
Annual variation of Sun–Earth distance	Lower atmosphere weather coupled through mesopause
Solar cycle variations (11 and 22 years)	Surface phenomena: earthquakes, volcanoes
Longer period solar epochs	
2. *Solar wind, geomagnetic activity*	4. *Electrodynamics*
Day-to-day 'low level' variability	Dynamo 'fountain effect' at low latitudes
Substorms	Penetration of magnetospheric electric fields
Magnetic storms	Plasma convection at high latitudes
IMF/solar wind sector structure	Field-aligned plasma flows to and from plasmasphere and protonosphere
Energetic particle precipitation and Joule heating	Electric fields from lightening and sprites

Table 2
Ap for groups of years grouped by annual mean $F_{10.7}$, with amplitudes and phases of Fourier components. Phases are given as month of maximum

Group (no. of years)	Years in group	$F_{10.7}$ range (mean)	Mean *Ap* (st. dev.)	Annual *Ap* *Amp* (ph)	Semiann. *Ap* *Amp* (ph)
Low (6)	1964/5/75/6/85/6	72–76 (74)	12 (9)	1.8 (2)	1.8 (3)
Low/medium (5)	1961/2/6/73/84	90–104 (98)	14 (12)	0.2 (—)	2.6 (3)
Medium (8)	1960/7–70/8/83/8	120–162 (146)	15 (13)	1.1 (4)	2.3 (4)
High (8)	1957–9/79–81/9–90	190–232 (208)	18 (15)	1.9 (6)	2.9 (3)
Rising (5)	1966/7/77/78/88	87–144 (124)	12 (11)	0.7 (5)	1.4 (4)
Falling (7)	1960–2/72/82–4	90–174 (124)	17 (14)	0.6 (10)	2.3 (4)
All (34)	1957–1990	72–232	15 (12)	0.8 (5)	2.2 (3)

geomagnetic storms, presents an intractable problem of scientific and practical importance. Despite its elusiveness, the variability should be explainable in terms of the same physical, chemical, and dynamical processes that control the quiet day latitudinal, seasonal and solar cycle variations and the storm behaviour.

In Table 1 we list a range of possible causes, broadly divided into four categories, and touch on many of them in this paper. These causes may act on the neutral air via pressure and temperature variations, or on the electrons and ions via electrodynamic processes, such as dynamo electric fields, or chemical changes. The effects of the protonosphere and plasmasphere are difficult to distinguish from those of geomagnetic activity, at least in our analysis, so we do not discuss them separately.

In this paper we first describe our sources of solar-geomagnetic and ionospheric data (Section 2), and then examine the variability of the solar index $F_{10.7}$ and the geomagnetic index *Ap* (Section 3) before proceeding to analyse the day-to-day variability of *NmF*2 at all seasons (Section 4). These topics need to be understood within the wider subject of 'space weather' (Section 5).

2. Ionosonde stations and solar-terrestrial data

This study is based on data from 34 years, 1957–1990. We group these years by their annual mean values of solar decimetric flux density at 10.7 cm wavelength ($F_{10.7}$), with additional groups of rising and falling $F_{10.7}$ to take account of any difference in geomagnetic activity between the rising and falling parts of solar cycles (Table 2). To represent geomagnetic activity we use daily and monthly values of *Ap*; the annual and semiannual Fourier components shown in this table are discussed in Section 3.1.

For the ionospheric analysis, we take F2-layer critical frequencies from the 1994 NGDC/WDC-A Ionospheric Digital Database (CD-ROM), National Geophysical Data

Table 3
Station Coordinates, listed in order of magnetic latitude, which is 'corrected geomagnetic latitude' at ground level for the present epoch. '*Diff*' = |*Geog Lat*| − |*Mag Lat*|. All values in degrees

STATION	*Geog Lat*	*Geog Long*	*Mag Lat*	*Diff*
Moscow	+56	+37	+51	+5
Wallops Is	+39	−77	+50	−11
Slough	+52	−1	+48	+4
Wakkanai	+45	+142	+38	+7
Tashkent	+41	+70	+37	+4
Djibouti	+11	+43	+2	+9
Huancayo	−12	−75	+2	+10
Vanimo	−3	+141	−11	−8
Brisbane	−28	+153	−37	−9
Port Stanley	−52	−58	−38	+14
Capetown	−34	+18	−42	−8
Hobart	−43	+147	−54	−11
Kerguelen	−49	+70	−58	−9

Center, Boulder, CO. We use data from 13 stations chosen to represent a range of latitudes and geographic/geomagnetic relationships (Table 3). These stations include both the 'near-pole' and 'far-from-pole' longitude sectors described by Rishbeth (1998) ('pole' meaning magnetic pole), the distinction being illustrated by the differences between geographic and corrected geomagnetic latitudes shown in the last column of the table. In 'near-pole' sectors, which are west longitudes in the northern hemisphere and east longitudes in the southern, the geomagnetic latitudes exceed the geographic latitudes, but the converse applies in 'far-from-pole' sectors, east longitudes in the northern hemisphere and west longitudes in the southern. Huancayo may appear to be an exception, but that is because of the way the signs are treated.

3. The annual and semiannual variation of geomagnetic disturbance

3.1. Variations of Ap

As a preliminary to studying ionospheric variability, we examine the seasonal variability of the solar-terrestrial parameters. Fig. 1 demonstrates in two ways the semiannual effect in the daily geomagnetic index.

In Panel (a) is shown the occurrence over the years 1932–1992 (Joselyn, 1995) of $Ap > 50$, which represents a strong geomagnetic disturbance. Over the 61 years of *Ap* summarized in panel (a), one extra $Ap > 50$ day per month in March, April, September and October is more than sufficient to account for the pattern shown. Panel (b) shows the month-by-month averages of *Ap*, the equinoctial maxima being 15–20% above the annual mean level of $Ap = 15$. For a single day per month to account for this pattern, a value of $Ap = 105$ is required, or two $Ap = 52$ days per month or three $Ap = 35$ days per month, etc. This seems most unlikely, so we conclude that the semiannual maxima in geomagnetic activity are not always due to one extra strong storm day per month, as Fig. 1(a) might imply, but to a cause that has a more prolonged time-scale.

We now analyse the monthly mean values of *Ap*, in groups of years described in Section 2, to obtain Fourier components in the form defined by the equation

$$Ap = Ap_0 + Ap_1 \cos((\pi/6)(t - \phi_1)) + Ap_2 \cos((\pi/3)(t - \phi_2)), \quad (1)$$

where t specifies the months and the phase ϕ represents the time of maximum, in months from December solstice. The results are shown in Table 2. The analysis included most of the years 1957–1990, grouped as shown in the table. Our general conclusions, consistent with analyses of geomagnetic variability (e.g., Cliver et al., 1996) are

- mean *Ap* increases with $F_{10.7}$;
- all groups show equinoctial maxima;
- there is no consistent annual component;
- falling parts of solar cycles are more active than rising parts.

3.2. Variations of $F_{10.7}$

In this paper we take $F_{10.7}$ as a proxy for the solar extreme ultraviolet radiation that produces F-layer ionization. Balan et al. (1993) plotted the variation with $F_{10.7}$ of the fluxes of several important spectral lines and continua at wavelengths from 30 to 102.6 nm, and for the integrated flux over the range 5–105 nm. In each case the relation is linear over the range 70–200 of $F_{10.7}$, which covers all but the upper part of the 'high' group of years in Table 2. We conclude that $F_{10.7}$ is a satisfactory indicator for long-term variations (year-to-year, possibly month-to-month).

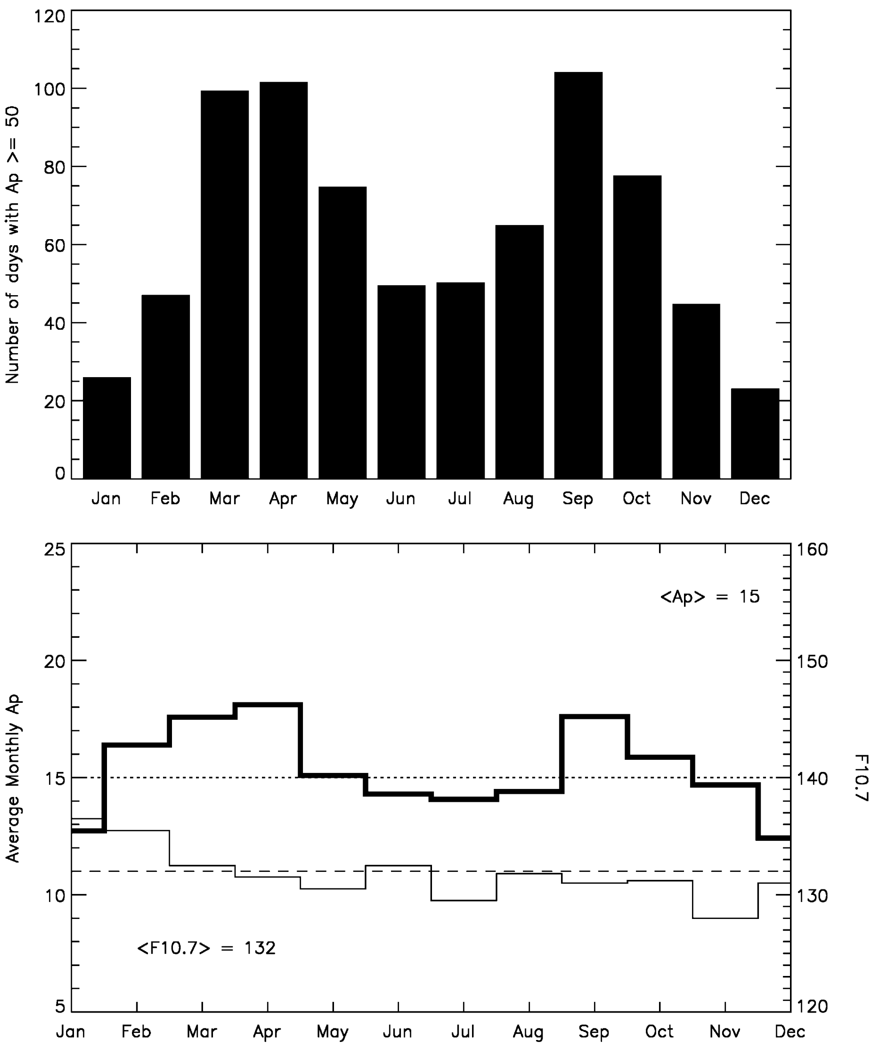

Fig. 1. (a) Monthly occurrence of daily $Ap > 50$ during 1932–1992, after Joselyn (1995). (b) Month-by-month variation of monthly average *Ap*, 1957–1995 (heavy line) and solar decimetric radio flux, 1957–1990 (thin line). The overall averages are shown as $\langle\ \rangle$.

$F_{10.7}$ is a property of the Sun. Conventionally, the tabulated values are corrected for the varying Sun–Earth distance and so, if averaged over many 27-day solar rotations, should not vary with time of year provided any instrumental or observational effects are removed. To test this, the thin line in Fig. 1(b) shows the overall month-by-month averages of $F_{10.7}$ for the 'low', 'low/medium', 'medium' and 'high' activity groups of years. The variation is small for most of the year, but there are higher values in January and February, to which we attach no importance as they can be traced to individual years in the 'low/medium' and 'medium' groups of activity. Reassuringly, Fourier analysis of $F_{10.7}$ (not shown here) reveals no annual or semiannual components that we could regard as significant. There is a small but spurious annual effect in the years of 'rising' and 'falling' $F_{10.7}$, but that is merely a consequence of the rising or falling trend during these years.

3.3. *Day-to-day variability of Ap and* $F_{10.7}$

The values of *Ap* and $F_{10.7}$ given in Table 2 are average monthly values. In order to discuss day-to-day variability in the ionosphere, we need some measure of how they vary from day to day within a single month, so we computed the standard deviations σ of daily values within every month in our chosen groups of years.

In the case of $F_{10.7}$, for the 'low activity' years the standard deviation is 5%, corresponding to ± 4 flux units. For the other groups of years, the standard deviations range from 10% for the 'low/medium activity' years to 13%. The actual standard

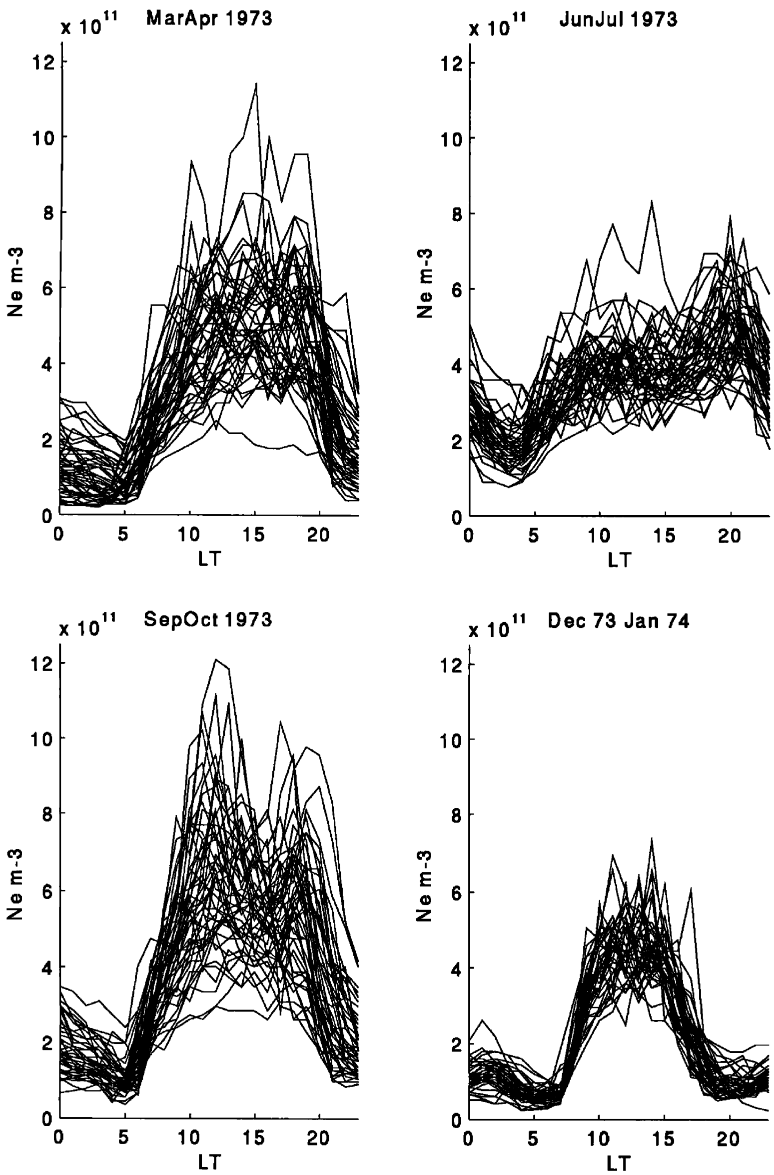

Fig. 2. Variation of *NmF*2 at Slough for every day during four 2-month periods in 1973/1974.

deviation $\sigma(F_{10.7})$ increases with increasing $F_{10.7}$, being for example $\sigma(F_{10.7}) = 17$ flux units for the 'medium activity' group of years. In the case of *Ap*, the percentage day-to-day variability is very much greater. The standard deviation is no less than 75% for the 'low activity' years, corresponding to $\sigma(Ap) = 9$ (as shown in the 'Mean *Ap*' column of Table 2). For all other groups the standard deviations are 80–90% of the mean values which, for a mean *Ap* of 15, implies a standard deviation $\sigma(Ap) = 13$.

These standard deviations themselves fluctuate from month to month, typically by 20% or so for both $F_{10.7}$ and *Ap*, but these fluctuations are not systematic with time of year. This is certainly to be expected in the case of the solar parameter $F_{10.7}$, but it applies to *Ap* as well. The fluctuations probably arise because individual extreme events are not fully averaged out over the 34-year datasets.

4. Ionospheric day-to-day variability versus season

4.1. Variability at Slough

We start by studying variability of *NmF*2 at Slough, a typical midlatitude station with a large summer/winter difference. Fig. 2 shows the local time variation of *NmF*2 in

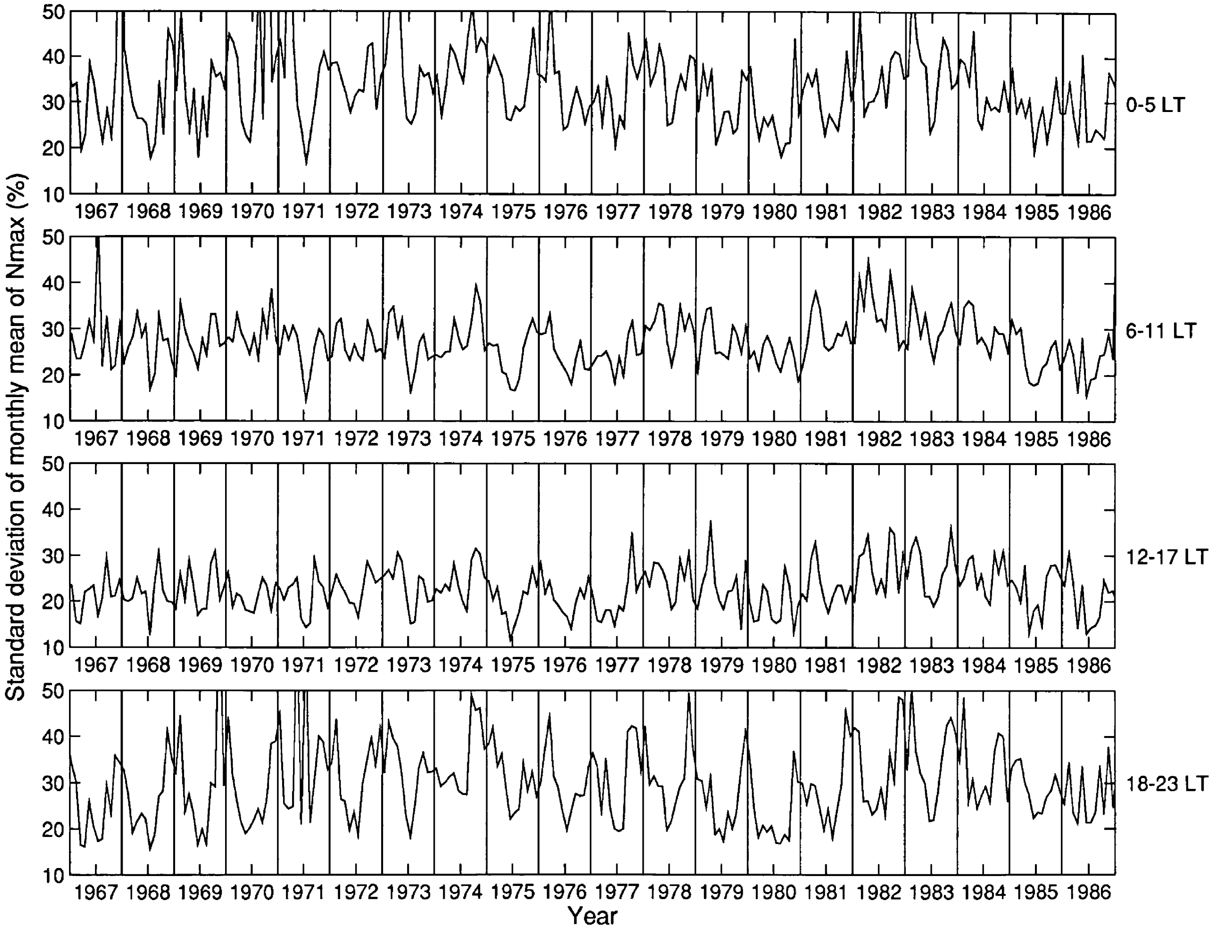

Fig. 3. Percentage standard deviations from monthly means, $\Sigma(NmF2)$, of individual daily values of Slough $NmF2$ for 1967–1986, divided into four ranges of local time.

four seasons at Slough in 1973/1974, each 'season' comprising two calendar months. With monthly $F_{10.7}$ in the range 84–102 and moderate mean values of Ap, these data represent 'low/medium' activity, except in March and April which were fairly disturbed. Inspection of the four panels of Fig. 2 reveals a strong semiannual pattern, the equinox periods having more day-to-day fluctuations than the solstice periods. Monthly mean curves of $NmF2$ show a repeatable progression over a year, and also throughout solar cycles. There is considerable day-to-day variability about the monthly means, characterized by the standard deviation $\sigma(NmF2)$.

Inspection of Fig. 2 shows that $\sigma(NmF2)$ is on the whole greater around midday than by night, and is greater at equinox than at solstice. Although the absolute standard deviation is important in practical applications, for our purposes we prefer to express it as a percentage of the mean value of $NmF2$,

$$\Sigma(NmF2) = \sigma(NmF2)/NmF2\ (\%). \quad (2)$$

We drop the parenthesis ($NmF2$) when the meaning seems clear from the context. As for significance, changes of 5% in Σ are regarded as worthy of notice.

Fig. 3 illustrates the nature of ionospheric variability by showing, month by month for the 20 years 1967–1986, the variability $\Sigma(NmF2)$ of individual daily values of $NmF2$ in four bins of local time (00–05, 06–11, 12–17, 18–23 LT). Many of the panels show a semiannual pattern, particularly in daytime bins, though there is no obvious solar cycle variation. Fig. 4 shows the variation with season of $\Sigma(NmF2)$ for the midday 10–16 LT bin. Again there is a semiannual pattern, the distributions in spring and fall having the highest mean levels and the broadest distributions of variability. Comparing this with results for other LT bins (not shown), we find this pattern is most consistent during daytime, which best represents the combined effects of production, loss and dynamics, and is least affected by the seasonal changes in sunrise/sunset times, which also contribute to the statistical variability in LT bins that include dawn and dusk. Taken together, Figs. 2–4 show that, at a single but typical mid-

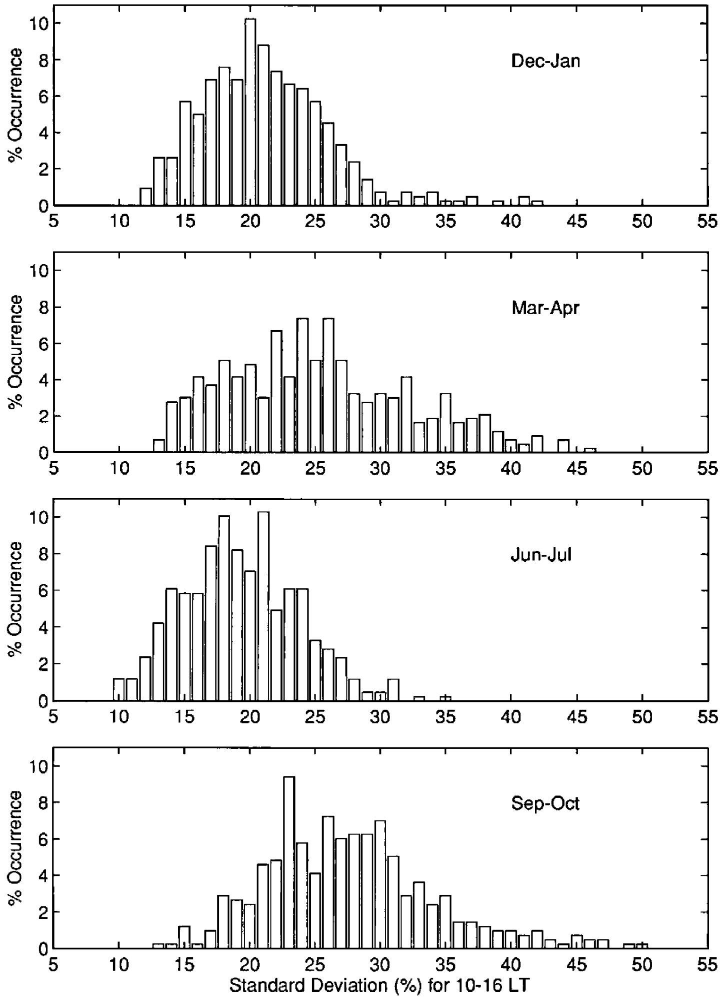

Fig. 4. Distribution of percentage values of Slough $\Sigma(NmF2)$ shown in Fig. 2.

latitude station where the summer/winter changes are well defined, the day-to-day variability of $NmF2$ is greatest in equinox months.

The mean values of $NmF2$, $\sigma(NmF2)$ and $\Sigma(NmF2)$ for these periods, and for the corresponding 2-month periods at solar maximum (1979/1980), are shown in Table 4, values for each month being shown separately. The differences between March and April, and between September and October, are mostly due to the transitions between summer and winter. By day, both absolute and percentage standard deviations, $\sigma(NmF2)$ and $\Sigma(NmF2)$, are greater at equinox than at solstice (except for the large σ in December 1979, which is associated with the extremely high and variable $NmF2$). At night, $\Sigma(NmF2)$ shows equinoctial maxima in 1973, but its behaviour in 1979/1980 is less clear-cut. The extent to which the seasonal transitions of mean $NmF2$ contribute to day-to-day variability is discussed further in Section 4.4, where the data are described in more detail (the local time bins are centred on noon and midnight, 10–14 LT and 22–02 LT).

To show the year-to-year variations under similar solar conditions, at all local times, Fig. 5 shows for each month the standard deviations of the individual daily values of $NmF2$ at Slough, separately for six years in the ‘low/medium’ activity group.

4.2. Seasonal dependence of day-to-day variability at 13 stations

We now study the day-to-day variability in the 34-year period 1957–1990, for which the overall mean of solar activity lies in our ‘medium’ range (a few years had to be omitted for some stations). Figs. 6–8 show the average standard deviations for each calendar month at all 13 selected stations, for both day (10–16 LT) and night (21–03 LT) data. The

Table 4
Mean solar 10.7 cm flux and magnetic *Ap*, and values, standard deviations and percentage standard deviations of peak electron density *NmF*2, for monthly periods at Slough at solar minimum and maximum

Period	$F_{10.7}$	Ap	$NmF2$ 10^{10} m^{-3}	$\sigma(NmF2)$ 10^{10} m^{-3}	$\Sigma(NmF2)$ (%)
Day (10–14 LT)					
March/April 1973	99, 106	25, 30	50, 45	14, 13	28, 28
June/July 1973	94, 87	17, 12	42, 37	9.5, 6.0	23, 16
Sept/Oct 1973	96, 78	14, 18	54, 66	15, 18	27, 27
Dec 73/Jan 74	82, 81	11, 15	44, 44	8.3, 9.0	19, 21
March/April 1979	199, 175	15, 25	176, 109	53, 44	30, 41
June/July 1979	186, 171	12, 12	70, 69	16, 15	23, 22
Sept/Oct 1979	202, 216	14, 12	94, 202	27, 56	29, 28
Dec 79/Jan 80	197, 200	9, 10	224, 168	58, 32	26, 19
Night (22–02 LT)					
March/April 1973	99, 106	25, 30	12, 16	6, 9.5	49, 60
June/July 1973	94, 87	17, 12	32, 29	11, 9	34, 31
Sept/Oct 1973	96, 78	14, 18	21, 14	9.6, 5.3	45, 38
Dec 73/Jan 74	82, 81	11, 15	11, 11	3.3, 3.5	30, 32
March/April 1979	199, 175	15, 25	53, 45	15, 16	29, 35
June/July 1979	186, 171	12, 12	66, 60	15, 16	22, 26
Sept/Oct 1979	202, 216	14, 12	40, 45	9, 12	22, 26
Dec 79/Jan 80	197, 200	9, 10	21, 20	8, 8	37, 40

stations are grouped by magnetic latitude, in Fig. 6 for the five subauroral stations (N/S magnetic latitudes 58–48°), Fig. 7 for the intermediate stations (N/S magnetic latitudes 42–37°), and Fig. 8 for the low latitude stations (magnetic latitudes below 12°).

To provide some quantitative measure of variations throughout the year, we compute $\Sigma(NmF2)$ for the four 1-month periods centred on equinoxes and solstices. As phases cannot be derived from only four values, we simply show the annual mean value, the semiannual amplitude, and the summer/winter differences according to the equations

$$\text{Annual mean}: \Sigma_M = \{\Sigma(spring) + \Sigma(summer) + \Sigma(fall) + \Sigma(winter)\}/4, \quad (3a)$$

$$\text{Semiannual}: \Sigma_{SA} = \{\Sigma(spring) - \Sigma(summer) + \Sigma(fall) - \Sigma(winter)\}/2, \quad (3b)$$

$$\text{Summer/winter}: \Sigma_{WS} = \{\Sigma(winter) - \Sigma(summer)\}. \quad (3c)$$

Table 5 gives the numerical results. The annual means are generally greater by night than by day, and are smallest at intermediate latitudes. Averaged over all 13 statios, the 24-h average, daytime and nighttime variabilities are respectively 25%, 20% and 33%. These results are not identical with those of Figs. 6–8, because of the different data selection.

By day at most subauroral and intermediate stations, as may be seen on the left of Figs. 6 and 7, variability is rather greater in December/January than in June/July in both hemispheres so there is an annual effect. However, it is not very significant and Wallops Is is obviously an exception. Moreover, the summer/winter variation at subauroral stations, particularly Kerguelen, is masked by the strong equinoctial peaks. Thus, by day, the pattern is in concert with the semiannual variation of geomagnetic activity.

At night, as seen on the right of Figs. 6 and 7, the pattern is seasonal, with greater variability in winter than in summer—apart from Kerguelen, geomagnetically the highest latitude station in the set. Only Moscow and Kerguelen show pronounced equinoctial maxima at night. At the intermediate latitude stations (Fig. 7), the equinoctial effect is weak too, except at night at Port Stanley which has a rather special blend of geomagnetic and geographic coordinates.

We find no correspondence between the patterns of daytime *NmF*2, as demonstrated by Torr and Torr (1973), and of its day-to-day variability Σ. Of the midlatitude stations we use, only Port Stanley, Wakkanai and Brisbane show a predominantly semiannual variation of noon *NmF*2, and of these, only Wakkanai shows much sign of a semiannual trend in Σ. Conversely Moscow, Wallops Island, Slough and Kerguelen have a predominantly winter/summer variation of noon *NmF*2 (albeit with a midwinter dip) but equinoctial maxima of Σ. This lack of correspondence between the day-to-day variability Σ and the quiet-day behaviour of

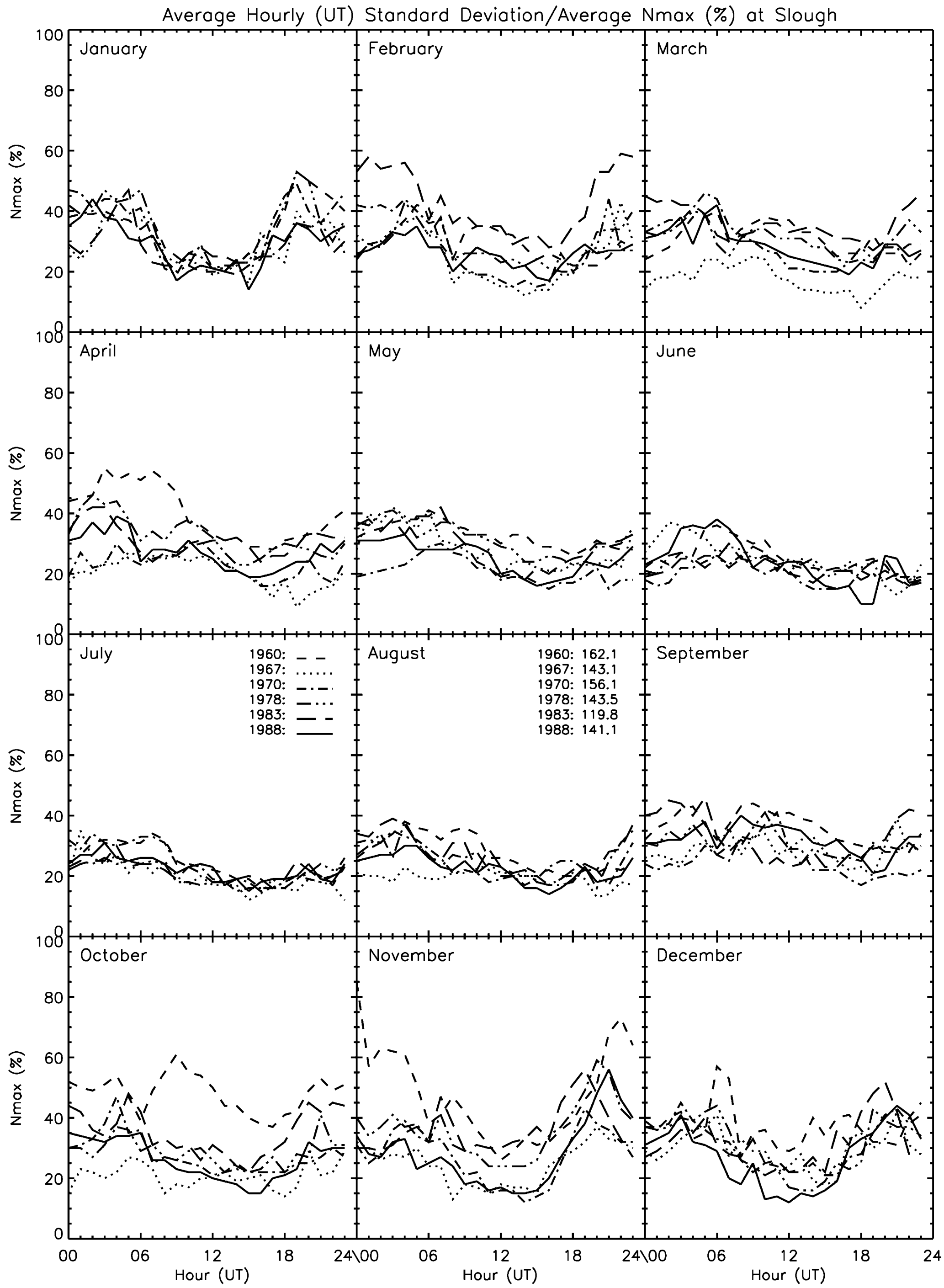

Fig. 5. Percentage standard deviations Σ of daily Slough *NmF*2 from monthly mean values versus local time, month by month for 6 years of medium solar activity (annual mean $F_{10.7}$ in the range 120–162).

*NmF*2 is not surprising, as the latter is mainly controlled by the global thermospheric circulation (Rishbeth, 1998), which has little to do with the solar wind/geomagnetic linkage to which the semiannual variation of *Ap* is attributed.

Fig. 8 shows results from three equatorial stations. By day, the variability is rather smaller than at most midlatitude stations, with no consistent seasonal pattern. At night the variability is greater than at midlatitudes,

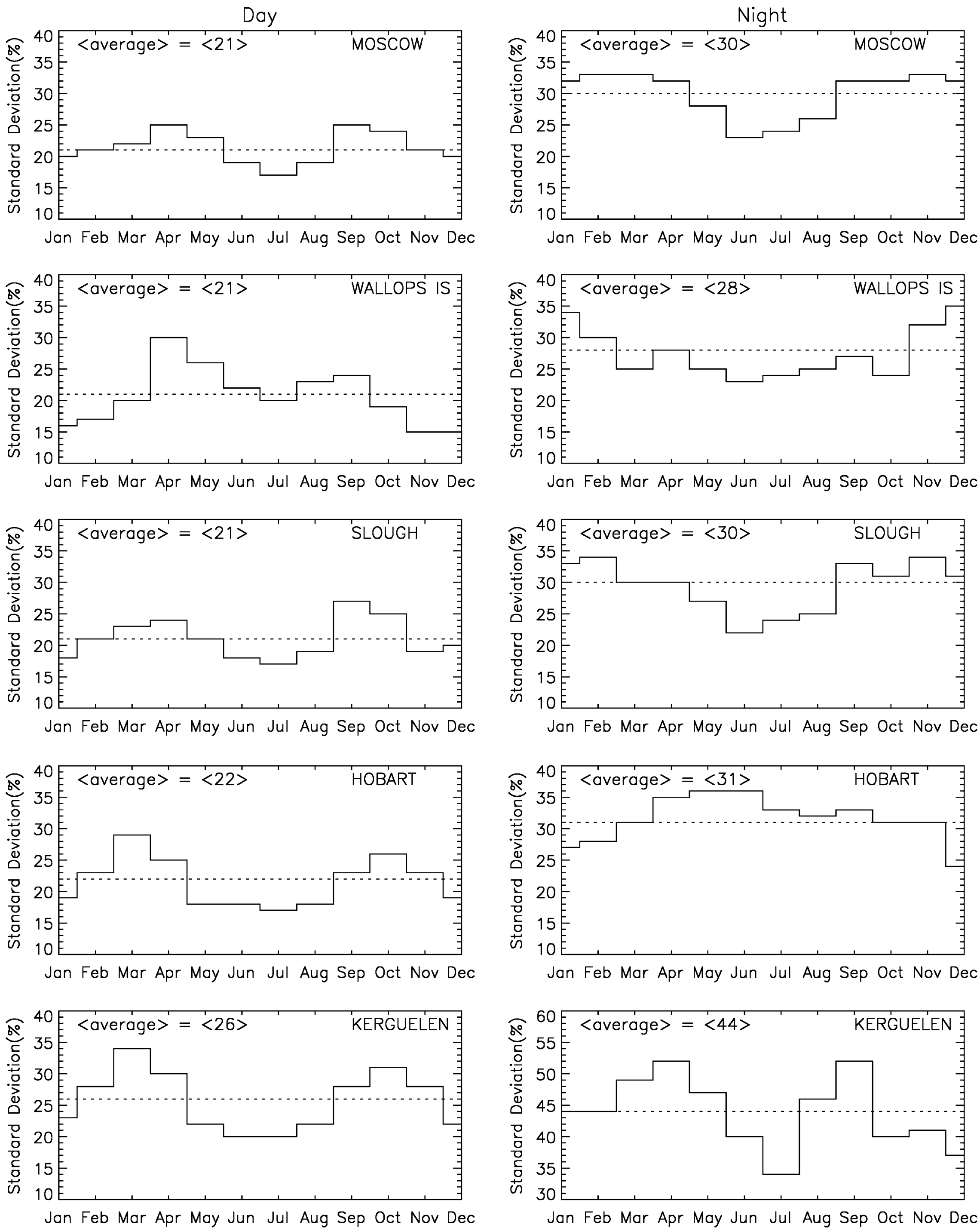

Fig. 6. Percentage standard deviations $\Sigma(NmF2)$ at five subauroral stations, averaged over 10–16 LT (left) and 21–03 LT (right) for calendar months, for all available years during 1957–1990.

with Vamino as the extreme case, very likely because of its situation on the flank of the equatorial zone with its highly variable dynamics (see also Forbes et al., 2000).

4.3. Calendar, geomagnetic and heliographic seasons

A persistent feature that emerges from the analysis above is the equinoctial maximum in ionospheric variability. We

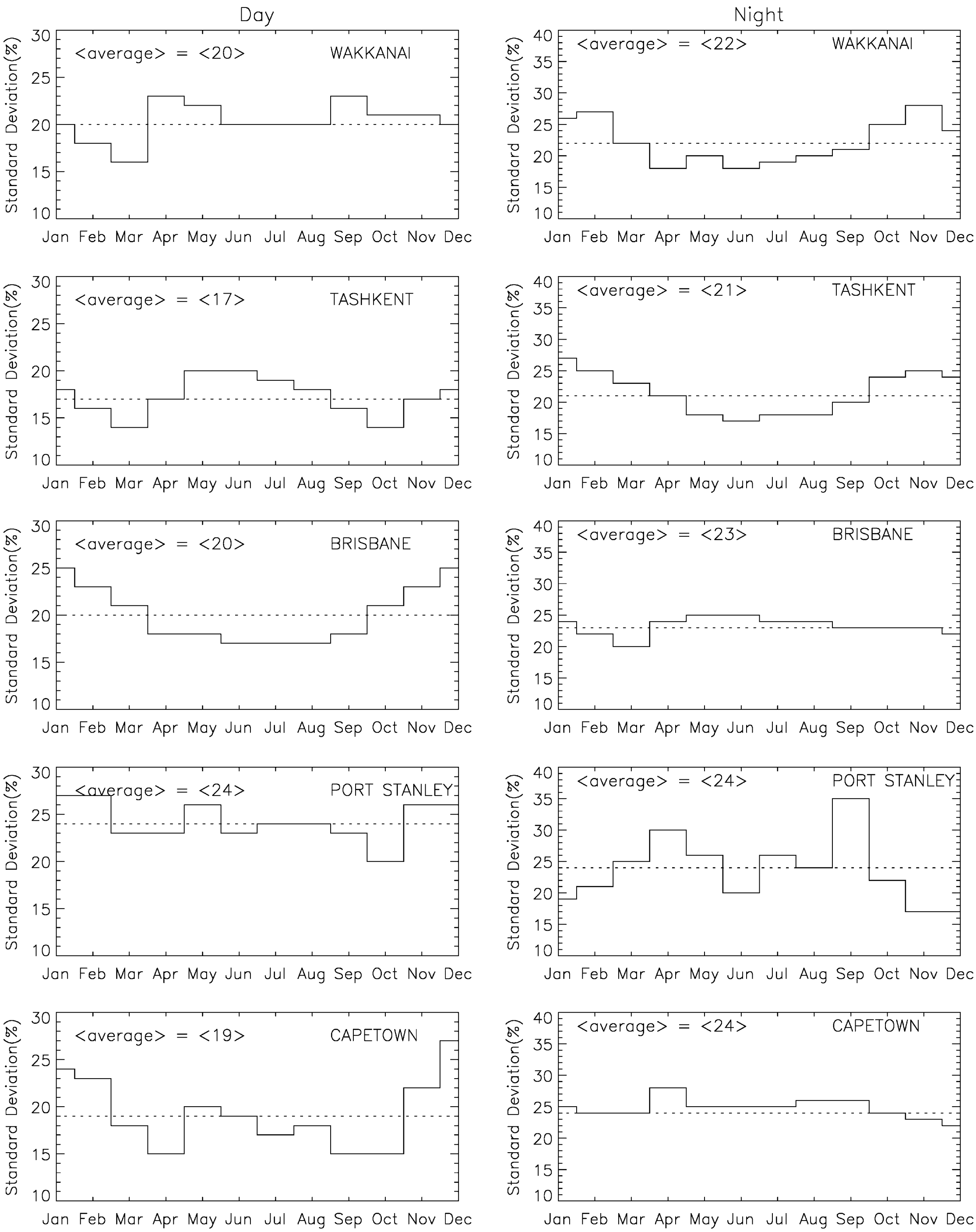

Fig. 7. As Fig. 6 for five stations at intermediate magnetic latitudes.

may reasonably ask if it has a possible connection with the semiannual pattern in geomagnetic activity, which was discovered decades ago, its cause being discussed by McIntosh (1959) and many subsequent authors, for example Joselyn (1995). Recent papers by Cliver et al. (2000) and Richardson et al. (2000) discuss the mechanisms. One explanation, quite widely accepted, is that on average the southward component of the IMF presents its largest mag-

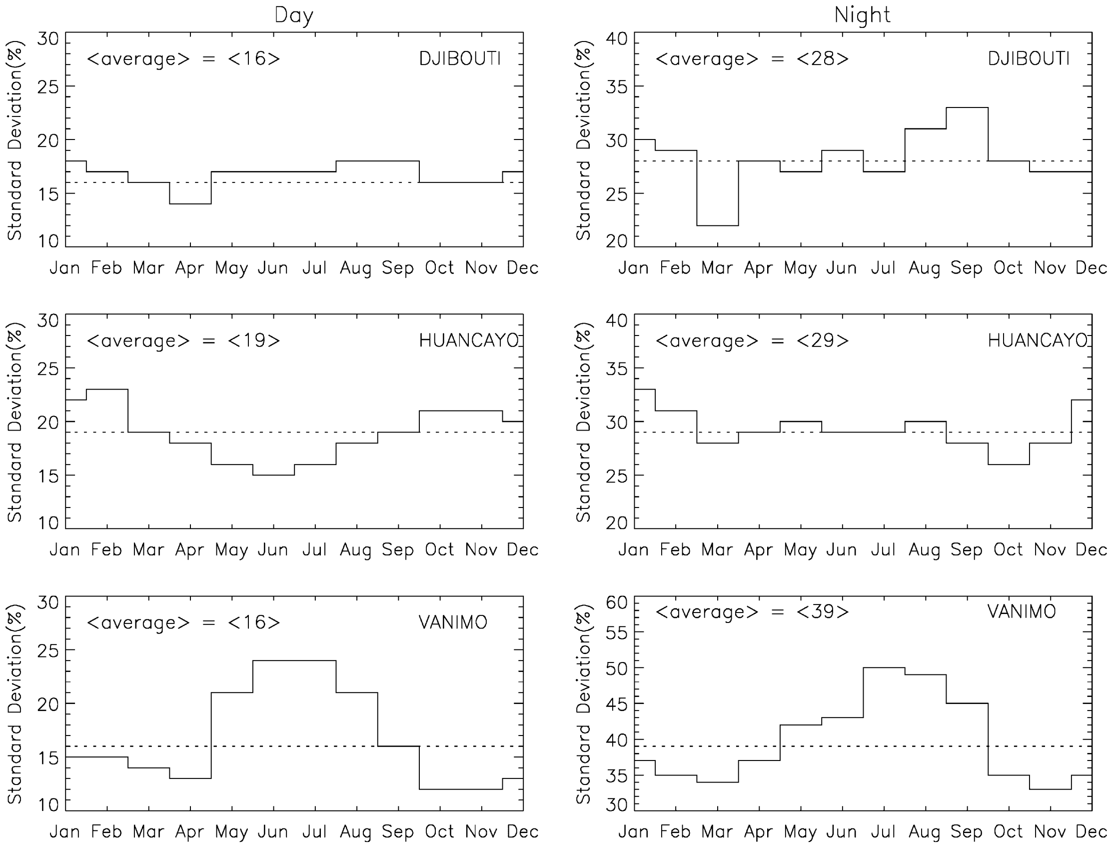

Fig. 8. As Fig. 6 for three stations at low magnetic latitudes.

Table 5
Variability of *NmF*2 (% standard deviation Σ from monthly mean) at 13 stations for 1957–1990. '*Mag Lat*' is 'corrected geomagnetic latitude'

Station	*Geog Lat*	*Mag Lat*	Annual mean Σ_M(%)			Winter–summer diff. Σ_{WS} (%)		Equinox–solstice diff. Σ_{SA} (%)	
			All	Day	Night	Day	Night	Day	Night
Moscow	+56	+51	27	21	30	+2	+10	+5	+5
Wallops Is	+39	+50	24	21	28	−5	+12	+4	−3
Slough	+52	+48	26	21	30	+1	+9	+7	+4
Wakkanai	+45	+38	23	20	22	+1	+7	0	0
Tashkent	+41	+37	20	17	22	0	+9	−3	0
Djibouti	+11	+2	23	17	28	−1	0	0	0
Huancayo	−12	+2	25	19	29	−5	−3	+2	−3
Vanimo	−3	−11	27	17	40	+11	+12	−4	−2
Brisbane	−28	−37	23	20	23	−9	+1	−2	−3
Port Stanley	−52	−38	25	24	24	−3	+6	0	+10
Capetown	−34	−42	23	19	25	−2	+7	−8	0
Hobart	−43	−54	26	22	31	−1	+13	+8	+2
Kerguelen	−49	−58	34	26	44	−2	+5	+11	+10

Table 6
Percentage day-to-day variability of Slough $NmF2$ versus length of data, using daily and nightly values of $NmF2$ averaged over 5 h as shown. The ± are typical values of the standard deviations of individual values in the 8–14 day range

Period	$F_{10.7}$	Ap	Day (10–14 LT)				Night (22–02 LT)			
Data length (days)			1	2	8–14	28	1	2	8–14	28
March/April 1973	102	28	11	18	25 ± 5	28	20	31	48 ± 13	60
June/July 1973	90	14	10	13	18 ± 5	21	26	29	32 ± 3	33
Sept/Oct 1973	87	16	11	16	23 ± 5	26	17	24	37 ± 8	45
Dec 1973/Jan 1974	81	13	13	16	18 ± 3	18	15	20	29 ± 3	29
March/April 1979	187	20	10	24	32 ± 6	35	17	22	30 ± 5	30
June/July 1979	178	12	8	17	21 ± 2	23	14	18	21 ± 2	23
Sept/Oct 1979	209	13	8	15	24 ± 8	42	12	17	24 ± 5	26
Dec 1979/Jan 1980	198	10	9	12	17 ± 3	25	13	22	35 ± 6	37

nitude for merging with the geomagnetic field on about 5 April and 5 October each year (Russell and McPherron, 1973). In principle, the Earth's heliographic latitude might also have some geophysical influence; the Earth passes through the Sun's equatorial plane on or near 5 March and 5 September each year and attains extreme heliographic latitudes of $+7°$ on or near 5 June and $-7°$ on 5 December. We have examined the semiannual variability patterns of using 31-day datasets centred on the 'traditional' (calendar), 'geomagnetic' and 'heliographic' definitions of seasons. We find that the semiannual variability of $\Sigma(NmF2)$ is slightly more pronounced if we use the Russell–McPherron dates to define 'geomagnetic' seasons, than with the 'heliographic' or 'calendar' dates, but this effect is limited to the subauroral stations. We conclude that datasets shorter than 31 days are needed to study the question properly, so we do not pursue this topic in the present paper.

4.4. How do the summer-to-winter changes affect variability near equinox?

All the results discussed in Sections 4.1 and 4.2 refer to 1-month or 2-month runs of data. In effect they assume that, within its day-to-day variability, $NmF2$ does not change systematically during the two months. This is not the case at equinox, so we now examine the variability Σ within shorter lengths of data, in order to study the questions: How does Σ depend on the length L of the dataset, in particular is it smaller for shorter periods? How is Σ influenced by any background of seasonal trend within the period under study?

We again chose Slough, where $NmF2$ changes rapidly in equinox months between the summer and winter levels and used the same periods as in Section 4.1 and Table 4. We obtained values of critical frequency $foF2$ from World Data Centre WDC-C1-STP for 'day' (10–14 LT) and 'night' (22–02 LT), interpolating over isolated gaps of 1–2 h and skipping any day or night with > 2 missing values. We ignored qualifying letters, which affect 10–20% of the data (mostly at night and depending on season); we justify this on the grounds that the qualifications that might in principle affect our analysis, namely those that indicate the tabulated data as being 'maximum' and 'minimum' values, occur in $< 3\%$ of our data.

Each 2-month period contains at least 56 days and nights of good data, of which we used the first 56 days and nights, having converted values of $foF2$ to $NmF2$. All the analysis described in this Section and Section 4.5 was done on these five-hour daily averages N_D for 10–14 LT and nightly averages N_N for 22–02 LT.

To study the seasonal trends, we first split every 56-day dataset into 7-day 'weeks', each containing $7 \times 5 = 35$ values of $NmF2$. By day, the overall trend is downward in spring, upward in fall, but the solstice periods are flatter. At night, the seasonal trend is opposite, $NmF2$ being greater on summer nights than winter nights. Averaged over the 56-day periods, the trends (i.e., the change between the 1st and 56th day of the period) are typically $< 0.5\%$ per day at solstice, 1.5% per day for the case of December 1979/January 1980 when solar activity varied considerably, and 2.5% per day at equinox. All these trends are much smaller than the day-to-day variability that we discuss below, showing they pose no great problem at solstices though equinoxes need more consideration. At night, the sequences of weekly averages are bumpy, and the overall trends are generally smaller than in the corresponding daytime data.

To see how the variability Σ differs for different blocks taken from the same 56-day dataset, we divided the 56-day datasets into K blocks, using several lengths L ranging from 1 to 56 days (or nights), so $K = 56$ for $L = 1$ day, $K = 28$ for $L = 2$ days, etc., with only one block ($K = 1$) for $L > 28$. For the shorter lengths ($L = 11$ down to 1 day), for which each 2-month period contains several blocks, we calculated the standard deviations of the Σ's for individual blocks. Typical values of these 'deviations of deviations' for mid-range lengths L are shown by an error bar on a typical point of each graph and numerically as ± values in Table 6.

For longer lengths, which contain so few blocks that standard deviations are not useful, we can get some idea of variability by taking different samples of data. For example, for length $L = 35$ days, we can take the block either at the beginning of the dataset (days 1–35) or at the end (days 22–56). For lengths which do not fit exactly into 56 days (namely $L = 17, 22, 35$ and 44 days), this provides two separate values of Σ; we found that the differences between them are consistent with the standard deviations of the Σ's for shorter lengths L.

Fig. 9 shows the variability Σ plotted on a logarithmic scale of L. In general Σ increases with increasing length L, the increase being quite sharp from $L = 1$ to 3 days and then slower. Most plots are almost flat over a wide range of L, with higher values of Σ at equinox than at solstice. Some plots show an upturn of Σ at longer lengths ($L > \sim 14$ days); these are found at equinox (sometimes by day, sometimes by night), and also in December 1979/January 1980, when solar activity changed considerably within the period. Table 6 gives numerical data for a few lengths L; the lengths $L =$ 1–2 days are discussed below in Section 4.5, $L = 8$–14 days are typical mid-range values, and $L = 28$ approximates to the monthly data used elsewhere in the paper. We conclude from Fig. 9 and Table 6 that in general

(1) the percentage standard deviation $\Sigma(NmF2)$ is greater at equinox than at solstice;
(2) Σ is usually greater at night than by day;
(3) seasonal trends in $NmF2$ contribute to Σ over periods longer than about 14 days;
(4) spring equinox in 1973 (to some extent in 1979 also) is active magnetically, with large Σ;
(5) there is otherwise no real difference between daytime Σ in 1973 and 1979;
(6) nighttime Σ, however, is greater in 1973 than in 1979;
(7) short-term changes of solar activity make little contribution to Σ; and
(8) fluctuations of Σ between short blocks of data are appreciable, but do not affect (1)–(7).

We conclude that the greater variability at equinox is inherent, and is only partly due to the seasonal trends of $NmF2$. Considering the peculiarities of Slough with its large summer/winter changes of $NmF2$, seasonal trends are likely to have even less effect on day-to-day variability at other midlatitude stations.

4.5. Two-day waves in Slough NmF2?

An interesting feature seen in Fig. 9 and Table 6 is that Σ decreases sharply from $L = 2$ to 1, which means that the variation within 5 h of a single day is noticeably less than day-to-day variations, even from 1 day to the next; the same applies to nights. This might possibly provide evidence of the presence of 2-day waves in $NmF2$, such as were found by Chen (1992), Yi and Chen (1993), Forbes and Zhang (1997) and Forbes et al. (1997) at several stations in low and middle latitudes. We looked for 2-day waves in every sequence of 30 or more *consecutive* daily or nightly values of Slough $NmF2$ (a station not used in the papers just cited). There are 14 such sequences in our eight 2-month periods (because of data gaps, we had to exclude day and night data of March–April 1979 and night data of December 1973/January 1974).

For each of these 14 blocks of data, we took all the differences ($\Delta_{EO} = N_E - N_O$) of adjacent even (E) and odd (O) days, and then derived a 'two-day amplitude'

$$\langle \Delta_{EO} \rangle / \langle (N_E + N_O) \rangle \tag{4}$$

(where $\langle\ \rangle$ denotes the mean value), and a 'signal-to-noise ratio' in which the 'signal' is the mean $\langle \Delta_{EO} \rangle$ and the 'noise' is the standard deviation $\Sigma(\Delta_{EO})$ of all the individual even–odd differences. The amplitudes are small ($\langle 0.05 \rangle$ and the signal-to-noise ratios do not exceed 0.4. Perhaps not surprisingly, most of the larger signal-to-noise ratios (0.25–0.4) are in the daytime data.

It is possible that the period of so-called '2-day waves' is not exactly two days, in which case coherence would be lost in long blocks of daily data, so we investigated whether noticeable 2-day waves exist in shorter blocks of data, of around 10 days. We found seven sequences in which the even–odd difference Δ_{EO} has the same sign over 10–12 days (but no longer than that), which is more than might be expected in our 16 months of day/night data if all day-to-day changes were completely random. For these seven sequences (three day, four night), the signal-to-noise ratios are 1–1.5 and the amplitudes are 0.05–0.13, so the 2-day waves are better defined than in the longer sequences. We conclude that 2-day waves do exist in the Slough F2-layer, but they are not particularly strong or prevalent, and they play no great part in the day-to-day variability of $NmF2$. More analysis would be needed to study the 2-day waves properly, taking account of complications due to geomagnetic activity.

5. Discussion

5.1. Overview

Table 1 showed some possible causes of F-layer variability. We may reduce them to three broad categories: 'solar' (to do with solar photon radiation), 'geomagnetic', and 'meteorological'. Shortening $\Sigma^2(NmF2)$ to just Σ^2, we may notionally write

$$\Sigma^2(total) = \Sigma^2(solar) + \Sigma^2(geomag) + \Sigma^2(met). \tag{5}$$

All we can do in this paper is to estimate the relative importance of these components, mainly for midlatitudes. Forbes et al. (2000) found that day-to-day variations of solar ionizing flux are not a major contributor to the variability of $NmF2$. Their analysis separated zones of latitude, but did not consider variations of local time and season. Our analysis gives us no reason to disagree with this conclusion,

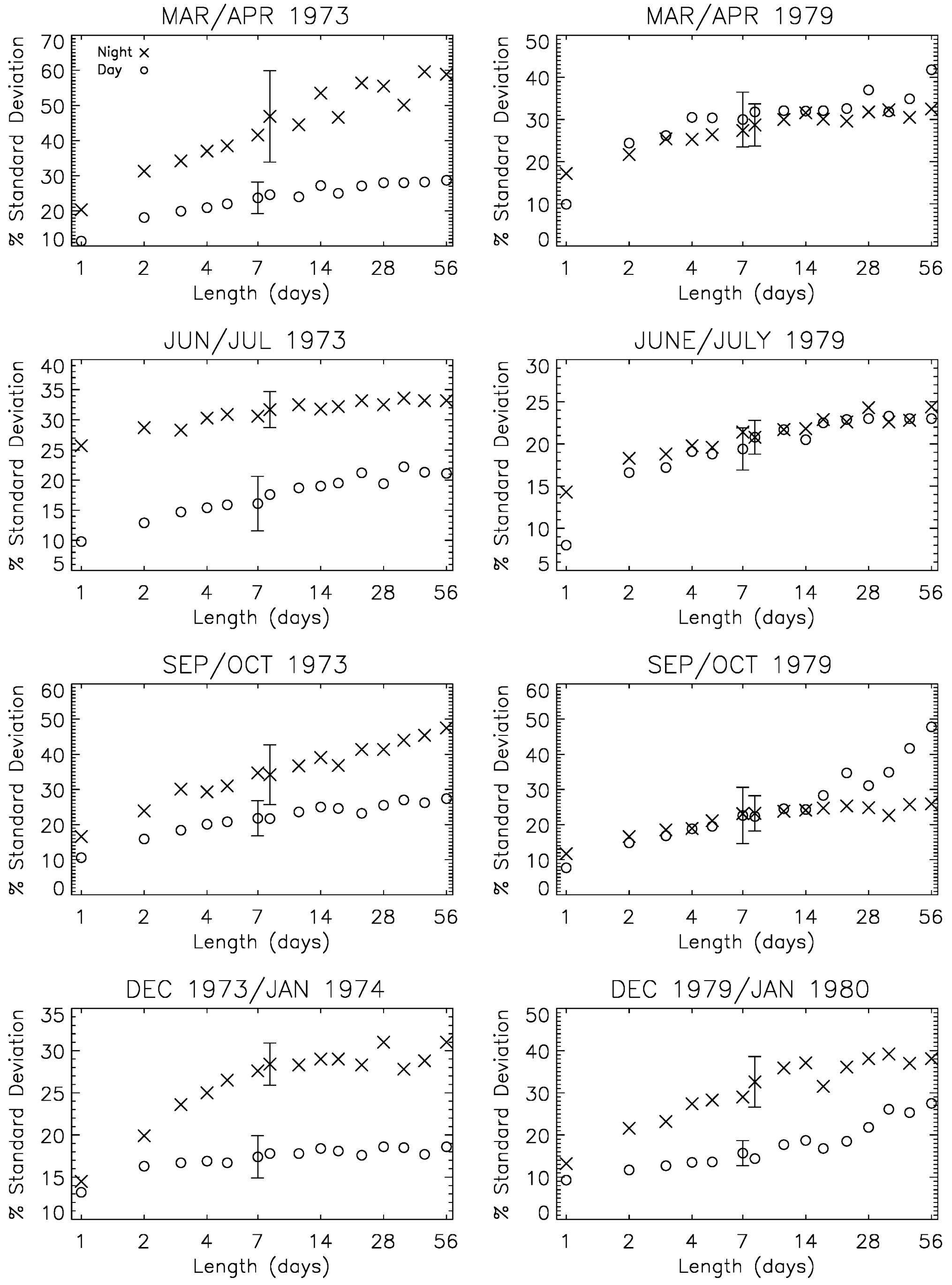

Fig. 9. Variability Σ versus length of dataset for 2-month periods at Slough. ‘Day’ (circles) 10–14 LT, ‘night’ (crosses) 22–02 LT. The bars show typical standard deviations of values of Σ for individual blocks of lengths 5–14 days.

which is consistent, for example, with the case study by Rishbeth (1993), who found little correlation between $NmF2$ and $F_{10.7}$ even in a period of high and variable solar activity (November–December 1979).

To this end, in Section 5.2 we try to estimate the sensitivity in terms of the percentage response of $NmF2$ to geomagnetic activity, using the results of Section 3.3. We suggested in Section 3.1 that the semiannual maxima in geomagnetic activity are not attributable to an extra big storm day per month, as Fig. 1(a) might imply, but rather to a more persistent cause, as indeed a geometrically driven mechanism should have. With geomagnetic activity susceptible to disturbances over such prolonged periods, the upper atmosphere should show signs of additional energy sources. The results displayed in Figs. 6–8 indicate that only the subauroral ionosphere shows evidence of a consistent equinoctial influence of geomagnetic activity. This is perhaps not surprising in that ionospheric storms are often most variable at subauroral sites, with positive phases (e.g., 'dusk effects') on the first day of a storm, followed by a negative phase of several days duration. The blend of thermal and electrodynamic forcing during any period of geomagnetic agitation would thus produce some level of F2-layer variability, primarily at upper midlatitudes.

5.2. Geomagnetic component of variability

In considering the '*geomag*' term in Eq. (5), we have to distinguish between the sensitivity of $NmF2$ to low level fluctuations of activity and its response to well-defined magnetic 'storms'. Concentrating for the moment on the former, we define a 'sensitivity' $S(geomag)$ of $NmF2$ (% per unit of Ap) as

$$\Sigma(geomag) = S(geomag)\sigma(Ap). \tag{6}$$

The results of Section 4.2 show that, to evaluate $S(geomag)$ at all accurately, we would have to consider place-to-place differences, particularly with latitude, and to use local magnetic indices (such as K-figures) instead of the global index Ap. All we can do here is to estimate $S(geomag)$ by using rough arguments based on our average results.

If we attribute the equinox/solstice differences of $\Sigma(NmF2)$ to the corresponding differences of geomagnetic activity, we can compare the semiannual amplitudes Σ_{SA} (Table 5) with the semiannual component of Ap, namely 2.2 units (Table 2). Averaging over all stations, we obtain an estimate of $S(geomag) = 1.5\%$ per Ap unit.

Additionally, using the results for Slough (Section 4.4 and Table 6), we can compare the active spring equinoxes in 1973 and 1979 with the adjacent quieter solstices. Again, results for individual equinoxes and solstices show a large scatter, but if we average the values of $\Sigma(NmF2)$ for all four equinoxes and subtract the corresponding average for all four solstices, and do the same for Ap, we estimate $S(geomag)$ as 1% by day and 2% at night per Ap unit.

This is at least consistent with the F2-layer effects of discrete magnetic storms. A great magnetic storm ($Ap = 100, Kp \sim 6$) usually causes a very severe decrease of $NmF2$ at midlatitudes (say 70%), which again implies a change of $NmF2$ by -1% per Ap unit. Combining our order-of-magnitude estimate of $S(geomag) \sim 1\%/Ap$ unit with the average variability $\sigma(Ap) \sim 13$ (Section 3.3), we deduce that

$$\Sigma(geomag) = S(geomag) \times \sigma(Ap) \sim 13\%. \tag{7}$$

5.3. Relative contributions to F2-layer variability

Using Section 5.2 we can estimate the 'meteorological' contribution to the total daytime variability of 20% from Eq. (5), discarding the solar contribution $\Sigma^2(solar)$ as being too small to matter, so that

$$\Sigma^2(met) = \Sigma^2(total) - \Sigma^2(geomag) = 20^2 - 13^2 \approx 15^2 \text{ (day)}. \tag{8}$$

Hence we ascribe 15% variability to 'meteorological' sources (plus the sum of the uncertainties in the other two sources; we must consider differences of one or two per cent as negligible). The corresponding calculation for night is probably too uncertain to be attempted. Recalling that Mendillo and Schatten (1983) also found that the variability on magnetic QQ days is in the range 13–18% for a 3-year dataset of daytime TEC values, 15% seems to be a reasonable characterization of 'solar-plus-meteorological' effects. If the solar component is only about 3%, essentially all this 15% variability must be attributed to 'meteorology'.

In summary, we suggest the 'meteorological' sources of F-layer variability are comparable to the 'geomagnetic' source and much larger than the 'solar' component. Forbes et al. (2000) also argue that the 'meteorological' and 'geomagnetic' sources are comparable (each 15–20% of $NmF2$), with the 'solar' source a minor contributor. Fuller-Rowell et al. (2000) quote a conclusion from a CEDAR workshop that all three sources contribute roughly equally, though their simulations tend to show a stronger effect from the 'geomagnetic' source. It seems that the 'solar' source is much more important for month-to-month and year-to-year variability of $NmF2$ than for day-to-day variability.

As for the nighttime F2-layer variability of 33%, we doubt whether the day-to-day solar variability can have any appreciable effect on a night-to-night basis. We surmise that nighttime variability is greater, partly because the absence of the strong daytime photochemical control renders the F2-layer more sensitive to 'geomagnetic' and 'meteorological' effects, but also because the 'geomagnetic' effect becomes stronger at night, when the auroral ovals become more active and move to lower latitudes.

5.4. Time constants

In this work we have, in effect, assumed that the geomagnetic variations occur with no time delay. In reality, we may expect a lag of at least some hours. Wrenn (1987) developed an 'accumulated time-lagged' magnetic index $Ap(\tau)$, to represent a time-delay in the ionospheric response, and found a best match to the ionospheric data with a time-lag of $\tau = 10$ h. Forbes et al. (2000) showed that the 'high frequency variability' (periods of hours to 2 days) and 'low frequency variability' (periods of days to weeks) respond to changes of Kp with time lags of order 6 and 12 h, respectively, so we conclude that day-to-day variations of *Ap* can be used for day-to-day indicators of geomagnetic activity.

Some of the processes listed in Table 1, such as electrodynamic effects and changes of solar ionizing radiation, may act almost instantaneously, but even in these cases the F2-layer takes a finite time to settle down to the changes, of order $1/\beta$ (where β is the ionization loss coefficient at the F2 peak), which is of order 1 h by day and 3–6 h at night. Changes of thermospheric composition are however slower to settle, and take days to do so; Aruliah et al. (2000) find a typical time-constant of 6 h at high latitudes for changes due to magnetic disturbance. We conclude that statistical treatments of variability, using 'same day' correlations with solar and geomagnetic indices, are a reasonable way to proceed. This would not be true of case studies of storm events, nor for seasonal global changes of thermospheric composition which take about 20 days to settle (Zou et al., 2000).

5.5. Comparison with previous work

There are several areas of comparison between the present study, the analysis by Forbes et al. (2000) and the modelling results of Fuller-Rowell et al. (2000). Using a database of $foF2$ values from 100 ionosondes (1967–1989), Forbes et al. fitted the values of $NmF2$ with temporal variability components ranging from hours to solar cycles, devising numerical methods of separating periodic components of variability. Extrapolating their regression analyses to 'zero geomagnetic activity' ($Ap = 0$) resulted in residual variability of about 25% for 'high frequencies' (hours to 2 days) and 15% for 'low frequencies' (2–30 days). Forbes et al. associated these levels of variability with 'meteorological' sources since they found little day-to-day correlations with $F_{10.7}$. Their 'low frequency' analysis used daily mean values, so they did not separate day and night, for which we find Σ to be significantly different. Thus we may consider their 'zero-*Ap*' variability of $\pm 15\%$ to represent both 'solar' and 'meteorological' sources.

The issues involved in transforming numerical models from climatology (monthly mean behaviour), to case studies of ionospheric storms and to models of day-to-day variability are well described by Fuller-Rowell et al. (2000). When models are given storm-time input parameters, they produce dramatic departures from ambient conditions, and indeed the results resemble actual ionospheric storm effects observed at various latitudes. The success is more visual than numerical; correlation coefficients between model and data are typically 0.3–0.65, depending on how the data are selected and smoothed.

6. Conclusions

In Section 4 of this paper we discussed the variability of the F-layer, which we quantified as the percentage standard deviation $\Sigma(NmF2)$. We found that $\Sigma(NmF2)$ is generally greater by day than at night, and greater at equinox than at solstice. We discussed variations of Σ between stations covering a wide range of latitude and longitude. Most of our results apply to a 34 year dataset (median $F_{10.7} \approx 140$), though we also analysed the variability at one station, Slough, for years of low and high solar activity (1973 and 1979), without finding any clear-cut difference between them. Admittedly, 1973 is not really a sunspot minimum year, nor magnetically quiet, but in Fig. 3 (which covers all the years 1967–1986), the variability in the actual sunspot minimum years (1975/6/85/6) is not much less than in other years. All our analysis leads to the general conclusion that we can assign broad average values of Σ of 20% by day and 33% at night, though the absolute standard deviations $\sigma(NmF2)$ are greater by day than at night. We believe that geomagnetic activity is a major cause of this variability, though 'meteorological' causes transmitted from lower levels may make a comparable contribution. To investigate this properly, it would be necessary to take account of regional differences, for example with latitude, and examine the data on a more local basis, using local magnetic indices (K-figures).

The principal systematic feature, found mainly at subauroral stations but to some degree elsewhere, is the semiannual pattern, with peaks at the equinoxes. There are differences between the solstices; in general, variability at night is greater in winter than in summer, but by day the variability is greater in December than in June in both hemispheres. In general, variability is somewhat greater at subauroral and equatorial latitudes than at midlatitudes. We examined the day-to-day variability at Slough within datasets of various lengths (1–56 days), and showed that it is fairly constant for data lengths of 5–20 days though, at equinox, the seasonal trends increase it at longer lengths. We found some evidence of 2-day waves.

We suggest that the greater variability at night, especially in winter, is partly due to the lower electron density, partly to the lack of the strong photochemical control that exists in the daytime F2-layer, but occurs largely because the auroral sources of magnetic activity become stronger and move to lower latitudes at night. This effect is enhanced in the winter when nights are long.

As for applications of our results: descriptions of F-layer variability are valuable for assessing the reliability of global ionospheric models. Yet, as Fuller-Rowell et al. (2000) point out, this success is often more qualitative than quantitative. When models use variable inputs appropriate to non-storm conditions, the ionospheric variability they produce is usually less than observed, and it cannot be claimed that the models meet a specific criterion such as '5% accuracy'. It is the blend of sources, together with their magnitudes and time histories, that need to be specified if models are to be more of practical use for 'space weather'. The renewed interest in ionospheric variability, as described here and in Forbes et al. (2000), is a step towards improving quantitative understanding of the upper atmosphere.

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References

Anderson, D.N., Buonsanto, M.J., Codrescu, M., Decker, D., Fesen, C.G., Fuller-Rowell, T.J., Reinisch, B.W., Richards, P.G., Roble, R.G., Schunk, R.W., Sojka, J.J., 1998. Intercomparison of physical models and observations of the ionosphere. Journal of Geophysical Research 103, 2179–2192.

Aruliah, A.L., Mueller-Wodarg, I.C.F., Schoendorf, J., 2000. Consequences of geomagnetic history on the high-latitude thermosphere and ionosphere: averages. Journal of Geophysical Research 104, 28 073–28 088.

Balan, N., Bailey, G.J., Jayachandran, B., 1993. Ionospheric evidence for a nonlinear relationship between the solar e.u.v. and 10.7 cm fluxes during an intense solar cycle. Planetary and Space Science 41, 141–145.

Banks, P.M., Kockarts, G., 1973. Aeronomy. Academic Press, New York.

Bremer, J., 1988. The influence of the IMF structure on the ionospheric F-region. Journal of Atmospheric and Terrestrial Physics 50, 831–838.

Bremer, J., 1996. The influence of high speed plasma streams on the ionospheric plasma. Journal of Atmospheric and Terrestrial Physics 58, 845–854.

Chen, P.-R., 1992. Two-day oscillation of the equatorial ionization anomaly. Journal of Geophysical Research 97, 6343–6357.

Cliver, E.W., Boriakoff, V., Bounar, K.H., 1996. The 22-year cycle of geomagnetic and solar wind activity. Journal of Geophysical Research 101, 27 091–27 109.

Cliver, E.W., Kamide, Y., Ling, A.G., 2000. Mountains versus valleys: semiannual variation of geomagnetic activity. Journal of Geophysical Research 105, 2413–2424.

D'Angelo, N., 1980. On the global scale electrodynamic coupling of high-latitude and low-latitude regions. Canadian Journal of Physics 58, 693–696.

DuCharme, E.D., Petrie, L.E., Eyfrig, R., 1971. A method for predicting the F1 layer critical frequency. Radio Science 6, 369–378.

Forbes, J.M., Zhang, X., 1997. Quasi 2-day oscillation of the ionosphere: a statistical study. Journal of Atmospheric and Solar-Terrestrial Physics 59, 1025–1034.

Forbes, J.M., Guffee, R., Zhang, X., Fritts, D., Riggin, D., Manson, A., Meek, C., Vincent, R.A., 1997. Quasi 2-day oscillation of the ionosphere during summer 1992. Journal of Geophysical Research 102, 7301–7305.

Forbes, J.M., Palo, S.E., Zhang, X., 2000. Variability of the ionosphere. Journal of Atmospheric and Solar-Terrestrial Physics 62, 685–693.

Fuller-Rowell, T.J., Codrescu, M.V., Moffett, R.J., Quegan, S., 1994. Response of the thermosphere and ionosphere to geomagnetic storms. Journal of Geophysical Research 99, 3893–3914.

Fuller-Rowell, T.J., Codrescu, M.V., Rishbeth, H., Moffett, R.J., Quegan, S., 1996. Response of the thermosphere and ionosphere to geomagnetic storms. Journal of Geophysical Research 101, 2343–2353.

Fuller-Rowell, T.J., Codrescu, M., Wilkinson, P., 2000. Quantitative modelling of the ionospheric response to geomagnetic activity. Annales Geophysicae 18, 766–781.

Johanson, J.M., Buonsanto, M.J., Klobuchar, J.A., 1978. The variability of ionospheric time delay. In: Goodman, J. (Ed.), Proceedings of the Symposium on the Effect of the Ionosphere on Space and Terrestrial Systems. Naval Research Laboratory, Washington, DC.

Joselyn, J.A., 1995. Geomagnetic activity forecasting: state of the art. Reviews in Geophysics 33, 383–401.

Kohl, H., King, J.W., Eccles, D., 1968. Some effects of thermospheric winds on the ionospheric F-layer. Journal of Atmospheric and Terrestrial Physics 30, 1733–1744.

McIntosh, D.H., 1959. On the annual variation of magnetic disturbance. Philosophical Transactions of the Royal Society of London A 251, 525–552.

Mendillo, M., Schatten, K., 1983. Influence of solar sector boundaries on ionospheric variability. Journal of Geophysical Research 88, 9145–9153.

Mendillo, M., Papagiannis, M.D., Klobuchar, J.A., 1972. Average behavior of the midlatitude F-region parameters NT, Nmax and τ during geomagnetic storms. Journal of Geophysical Research 77, 4891–4895.

Millward, G.H., Rishbeth, H., Moffett, R.J., Quegan, S., Fuller-Rowell, T.J., 1996. Ionospheric F2 layer seasonal and semiannual variations. Journal of Geophysical Research 101, 5149–5156.

Moffett, R.J., 1979. The equatorial anomaly in the electron distribution of the terrestrial F-region. Fundamentals of Cosmic Physics 4, 313–391.

Muggleton, L.M., 1972. A describing function of the diurnal variation of Nm(E) for solar zenith angles from 0 to 90°. Journal of Atmospheric and Terrestrial Physics 34, 1379–1384.

Pi, X., Mendillo, M., Fox, M.W., Anderson, D.N., 1993. Diurnal double maxima patterns in the F region ionosphere: substorm related aspects. Journal of Geophysical Research 98, 13677–13691.

Richardson, I.G., Cliver, E.W., Cane, H.V., 2000. Sources of geomagnetic activity over the solar cycle: Relative importance of coronal mass ejections, high-speed streams, and slow solar wind. Journal of Geophysical Research 105, 18 203–18 213.

Richmond, A.D., Ridley, E.C., Roble, R.G., 1992. A thermosphere–ionosphere general circulation model with coupled electrodynamics. Geophysical Research Letters 19, 601–604.

Rishbeth, H., 1993. Day-to-day ionospheric variations in a period of high solar activity. Journal of Atmospheric and Terrestrial Physics 55, 165–171.

Rishbeth, H., 1998. How the thermospheric composition affects the ionospheric F2-layer. Journal of Atmospheric and Solar-Terrestrial Physics 60, 1385–1402.

Rishbeth, H., Garriott, O.K., 1969. Introduction to Ionospheric Physics. Academic Press, New York.

Roble, R.G., Ridley, E.C., Richmond, A.D., Dickinson, R.E., 1988. A coupled thermosphere/ionosphere general circulation model. Geophysical Research Letters 15, 1325–1328.

Rush, C.M., 1976. An ionospheric network for use in short-term propagation predictions. Telecommunication Journal 43 (VIII), 544.

Rush, C.M., Gibbs, J., 1973. Predicting the day-to-day variability of the mid-latitude ionosphere for application to HF propagation predictions. AFCRL-TR-73-0335, Air Force Geophysics Laboratory, Hanscom AFB, MA, USA.

Russell, C.T., McPherron, R.L., 1973. Semiannual variation of geomagnetic activity. Journal of Geophysical Research 78, 92–108.

Torr, M.R., Torr, D.G., 1973. The seasonal behaviour of the F2-layer of the ionosphere. Journal of Atmospheric and Terrestrial Physics 35, 2237–2251.

Wrenn, G.L., 1987. Time-weighted accumulations $ap(\tau)$ and $Kp(\tau)$. Journal of Geophysical Research 92, 10125–10129.

Yi, L., Chen, P.-R., 1993. Long period oscillations in the equatorial ionization anomaly correlated with the neutral wind in the mesosphere. Journal of Atmospheric and Terrestrial Physics 55, 1317–1323.

Zou, L., Rishbeth, H., Mueller-Wodarg, I.C.F., Aylward, A.D., Millward, G.H., Fuller-Rowell, T.J., Idenden, D.W., Moffett, R.J., 2000. Annual and semiannual variations in the ionospheric F2-layer. I: a modelling study. Annales Geophysicae 18, 927–944.