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Study of Latitudinal variation of Ionospheric parameters - A Detailed report

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ABSTRACT
The ionospheric slab thickness is the ratio of ionospheric electron content (IEC) to the F-region peak electron density (NmF2). This has been analyzed during low solar activity period from January 2006 to December 2010. Hourly value of IEC and NmF2 by ionosonde technique is collected at Kwajelin (9^0N-167^0E), Learmonth (22^0S-114^0E); low latitude, Athens (38^0N-24^0E), Sanvito (40^0N-17^0E); mid-latitude and Chilton (52^0N-359^0E), Port_Stanley (52^0S-302^0E) high latitude location in the present study. The data and analysis method are classified in to 3 seasons including equinox (March, April, September and October), winter (January, February, November and December) and summer (May, June July and August). A detailed analysis of derived results is presented to bring into focus the latitudinal variations and utility of variations ionospheric parameters.

INTRODUCTION

The ionosphere plays a unique role in the Earth's environment because of strong coupling processes to region below and above. Its interface at low latitude 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 photochemical processes that govern the production and decay of the ionospheric plasma are reasonably well understood (Rishbeth and Garriot, 1969; Banks and Kockarts, 1973), and so are the roles of thermodynamics 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. Simple models that included production, recombination and diffusion, followed models of the F2-layer effects of thermospheric winds (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 (Fuller Rowell et al., 1994, 1996) and seasonal variations (Milliward et al., 1996, Zou et al., 2000). Knowledge of the IEC, ionospheric F2 peak density NmF2, its peak height hmF2, or in some cases the whole electron density profile Ne(h), is of great importance for ionospheric forecasting and ionospheric propagation studies. The ionospheric characteristics exhibit significant variations with solar cycle, season and local time, etc., which results from changes in the solar extreme ultraviolet (EUV) and X-ray radiations, and from various chemical and dynamic processes (Balan et al., 1994, Richards, 2001; Kawamura et al., 2002). Studies on the variations of these ionospheric characteristics are essential for ionospheric prediction and for understanding the physical mechanisms involved.

Over the past several decades, seasonal behaviors of the ionosphere have been explored with measurements of the F2 layer critical frequency foF2 (or maximum electron density NmF2), total electron content (TEC), and electron density Ne (Yuen and Roelfs, 1967; Mayr and Mahajan, 1971; Yonezawa, 1971; Moffett, 1979; Jakowaski et al., 1981; McNamara and Smith, 1982; Zou et al., 2000; Rishbeth et al., 2000; Ma et al., 2003; Yu et al., 2004). Ionosphere has also been explored with modelings (Milliward et al., 1996; Richards, 2001; Pavlov and Pavlova, 2005; Zeng et al., 2008). However, the question of seasonal variations of the ionosphere still has not been fully resolved (Rishbeth, 2004). The reason may be ascribed to the complexity of ionospheric seasonal variations, limitations of observation techniques, data coverage and also partly to the shift of interests from the ionospheric morphology to ionospheric dynamics. Furthermore, past works mainly focused on the patterns and underlying physical processes of the annual components as well as on the summer to winter and solstice to equinox differences (Wright, 1963; Ma et al., 2003; Mendillo et al., 2005; Zaho et al., 2005). Several authors have analyzed the annual, seasonal and semiannual anomalies of the ionosphere by using F2-layer peak electron content (NmF2) and TEC (Rishbeth, 1998; Rishbeth et al., 2000; Zaho et al., 2005; Meza and Natali, 2008; Liu et al., 2009). Recently, Ren et al., (2011) investigated the equinoctial asymmetry of the ionospheric vertical EXB plasma drifts velocity in the equatorial F-region and found that the equinoctial asymmetry depends on the local time. The asymmetry in daytime ionospheric vertical EXB plasma drift may relate to the equinoctial asymmetry in the E- region. Based on the ionospheric electron content density profiles and TEC data, Liu et al., (2010) investigated the equinoctial asymmetry of the daytime ionosphere during low solar activity. Venkatesh et al., (2011) studied the diurnal, day to day, seasonal and latitudinal variation of TEC, NmF2, slab thickness (τ) and neutral temperatures (Tn) over the three different Indian stations. Their result shows that the maximum electron density of the F2-layer (NmF2) at all the three stations more or less show similar nature of variation with much lower values during most of the day-time compared to those of TEC. The ionospheric electron content (IEC), maximum electron density and ionospheric slab thickness (τ) are the parameters used to monitor the temporal and spatial behavior of the ionosphere. The ionospheric slab thickness (τ) is defined (Davies, 1990) as the ratio of the ionospheric electron content (IEC) to the maximum ionospheric F2-layer electron density (NmF2), or in terms of the F2-layer critical frequency (foF2). In other words, τ represents the equivalent slab thickness (EST) / depth of an idealized ionosphere, which has the same electron content as the actual ionosphere. But it has uniform electron density equal to the maximum electron density.

Slab thickness measurements offer substantial information on the shape of the electron density profile, the neutral and ionospheric temperature gradients, the ionospheric composition and dynamics (Titheridge, 1964; Amayenc et al., 1971; Titheridge, 1973; Fox et al., 1990; Davies and Liu, 1991). Various studies indicated the close relationship between the ionospheric slab thickness and the vertical scale height (Wright, 1960; Furman and Prasad, 1973; Stankov and Jakowaski, 2006). The diurnal, day to day and seasonal variations of ionospheric slab thickness in the low and mid-latitudes of Indian region were studied by few Indian groups (Das Gupta et al., 1975; Bhuyan et al., 1986 and Prasad et al., 1987). Studies of diurnal variation of electron content and EST are useful to investigate the physical processes responsible for the ionospheric behavior (Pandey et al., 2001) and their descriptions are induced in ionospheric models such as International Reference Ionosphere (IRI) (Bilitza, 1990). The slab thickness values can be deduced from ionospheric models (empirical or otherwise) capable of providing vertical density profiles. So, the focus was on improving the existing ionospheric models rather than developing a stand – alone model of the slab thickness on a global scale.

Slab thickness contains the information regarding the neutral temperature (Titheridge, 1973) of the ionosphere and it depends on the scale height of the ionizable constituents and the scale height of loss processes, both of which are dependent on neutral temperature. The relationship between slab thickness and electron temperatures has also been reported by Mahajan et al., (1968). Although Furman and Prasad (1974) suggested that even though τ in general depends upon the plasma scale height it is not a good indicator of either electron or ion temperature. Minakoshi and Nishimutha (1994) have studied τ and shown that a large peak during pre-sunrise at solar minimum disappears as the sunspot number increases in the mid-latitude. Furthermore, this peak begins to reappear at the solar maximum, particularly during winter months. Titheridge, (1973) suggested that the pre-sunrise peak in τ may be due to the downward movement of the ionosphere when the neutral winds that have been maintaining the ionosphere decreases or reverse. The early morning peak in τ may also appear due to the fact that sunrise is earlier at heights above the F2 – layer, causing some production at the topside. This tends to give ionospheric electron content a lead over NmF2, which is still decaying.

The post-sunset increase in τ values during the different seasons under varying solar activity conditions at low latitude is due to the secondary fountain effect caused by the post-sunset occurrence of a strong eastward electric field existing over the equatorial latitudes (Bhuyan, 1986; Modi and Iyer, 1989 and Balan and Bailey, 1995). The post-sunset enhancement in the τ values observed at mid-latitudes (Minakoshi and Nishimutha, 1994) may also be associated with the nighttime enhancement events in total electron content, which is mainly due to the field aligned plasma flow from the protonosphere to the ionosphere.

The ionospheric monitoring capabilities of the slab thickness remain largely unexplored, despite the fact that, operationally, it is a very useful parameter as it allows a simple conversion between foF2 and IEC. Additionally, it is closely related to other important ionospheric characteristics. From this aspect, various possibilities exist for utilizing the ionospheric modeling/ monitoring efforts. For example, with instantaneous access to data from regional/ global digital ionosonde and GNSS reference networks, it would be possible to provide regional/global monitoring of the slab thickness in real time. This is achievable, considering that various space weather related services have already been established (Jakowski et al., 2005; Belehaki et al., 2006; Crespon et al., 2008).

If available in real time, over a region of interest the operational slab thickness and NmF2 monitoring can be used for characterizing and eventually predicting the ionospheric density distribution/ gradients, the extent of ionospheric density anomalies and their propagation characteristics (Stankov ei al., 2005). From this aspect, it is believed that the permanent ionospheric monitoring of slab thickness and NmF2 can assist various GNSS applications, such as improving the integrity and performance of network RTK positioning services, the ionospheric threat identification/estimation in aircraft navigation, etc. (Stankov and Jakowaski, 2006, 2007; Pullen et al., 2008; Stankov et al., 2009).

DATA AND METHOD OF ANALYSIS

Hourly value of ionosonde IEC and foF2 data are collected from the site NGDC Space Physics Interactive Data Resource (SPIDR) [http://ngdc.noaa.gov/] for low to moderate solar activity period i.e. from January 2006 to December 2010. Quiet days and disturbed days are taken from World Data Center Kyoto, Japan. The co-ordinates of the station used in the present study are as follows:

TABLE-1

STATION	GEOGRAPHIC LATITUDE	GEOGRAPHIC LONGITUDE
Chilton	52^0N	359^0E
Sanvito	40^0N	17^0E
Athens	38^0N	24^0E
Kwajelin	09^0N	167^0E
Port_Stanley	52^0S	302^0E
Learmonth	22^0S	114^0E

The peak electron density NmF2 for each hour is computed using the relation

$NmF2 = 1.24*(foF2)^2 *10^{10}$ el.m^{-3}, where foF2 is in MHz

The slab thickness τ, in km, for each hour is computed by τ = IEC/NmF2.

The data and analysis methods are classified in to 3 seasons including equinox (March, April, September and October), winter (January, February, November and December) and summer (May, June, July and August).

RESULTS

Diurnal variation of NmF2 and slab thickness (τ):

Figure 1 and 2 represents the diurnal variation of NmF2 and slab thicknesses (τ) for six locations, namely Chilton, Port_Stanley, Athens, Sanvito, Kwajelin and Learmonth from different latitudinal sectors. It may be seen that variation of NmF2 and slab thickness is maximum during day time hours at all the latitudes. The high value of slab thickness during the daytime is consistent with electrodynamic drift (fountain effect), which enhances the content

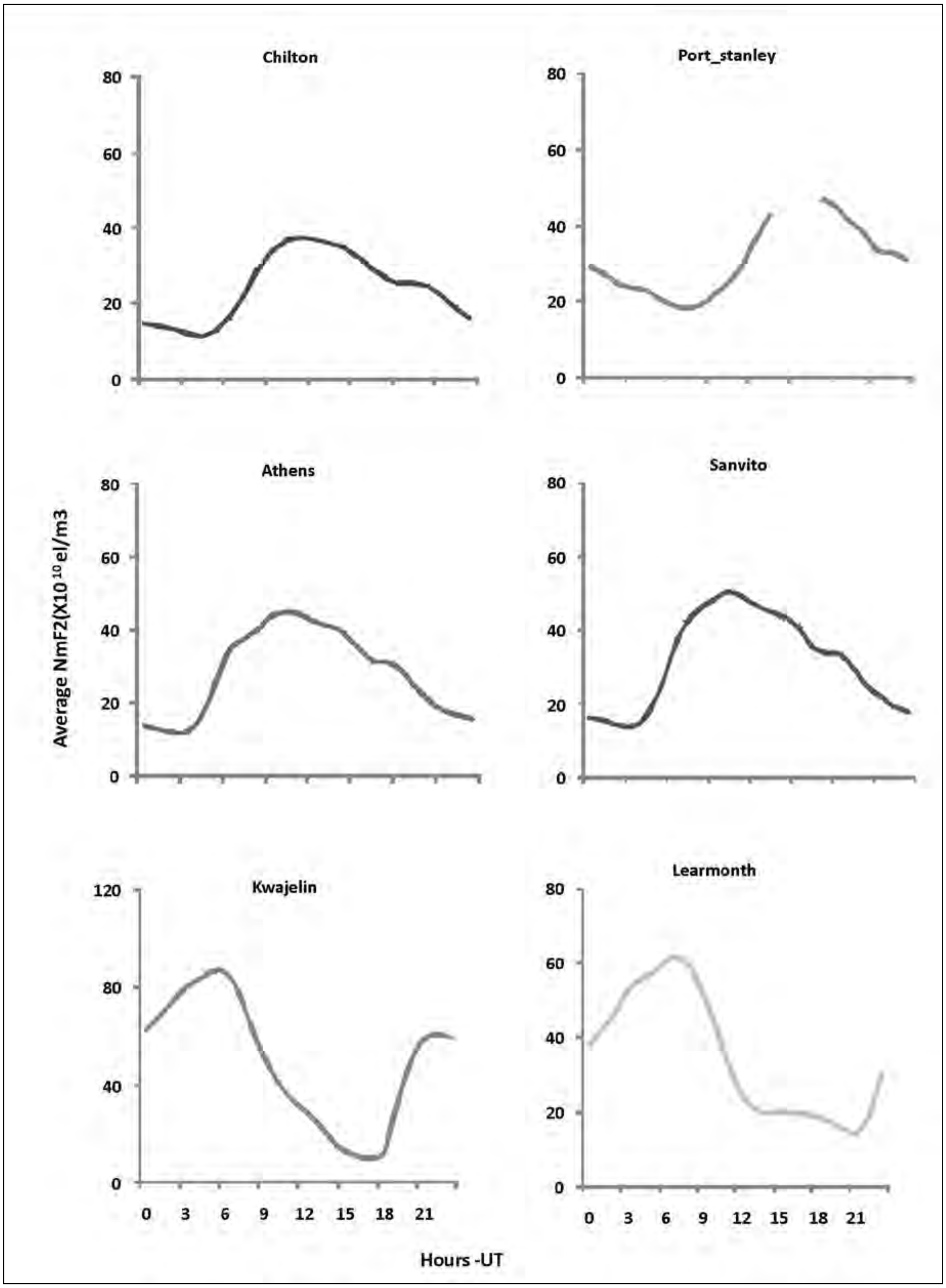

Figure 1. Diurnal Variation of NmF2

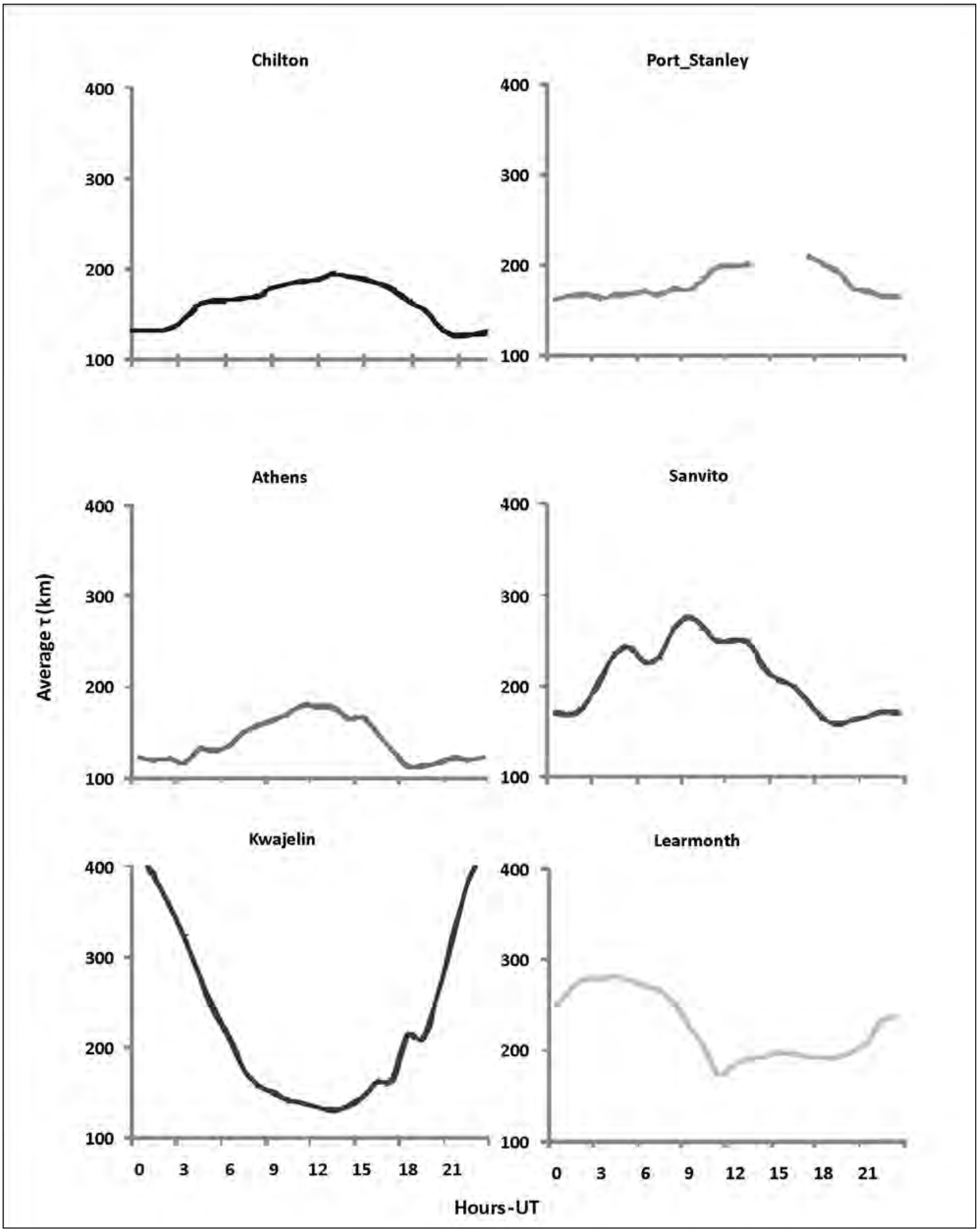

Figure 2. Diurnal Variation of TAU (km)

of the topside. The decrease in the value of slab thickness after 2200 hours may be due to the movement of the equatorial ionosphere to lower altitudes around this time. At Athens and Sanvito a significant early morning increase in slab thickness, with a minimum value varying from 100-250 km was observed. As pointed out in the introduction the presunrise peak in τ and early morning peak in τ have direct relation with ionospheric dynamics.

Seasonal variation of NmF2 and slab thickness (τ):

Figure 3 and 4 represents the seasonal variation of NmF2 and τ. It can be seen from the plots that NmF2 and τ shows a sharp day minimum around 0500 hours, (LT), and a broad day maximum during all the seasons at high, mid and low-latitude locations. At high latitude location Chilton, variation of NmF2 is maximum during equinox months and slab thickness during summer months whereas at same latitude Port_Stanley variation of NmF2 and slab thickness both are maximum during winter months. At mid-latitude location Athens variation of NmF2 is maximum during equinox months and slab thickness during summer months. At Sanvito variation of NmF2 is maximum during summer months and slab thickness during equinoxial months. At low latitude Kwajelin variation of NmF2 is maximum during winter months. A peak is noticed around 0500 hours, (LT), whereas the slab thickness is maximum during summer months. At Learmonth variation of NmF2 and slab thickness both are maximum during winter months.

Monthly variation of NmF2 and slab thickness (τ):

Figure 5 and 6 represents the monthly variation of NmF2 and slab thickness. Plots shows that variations of NmF2 and τ is smooth and constant at mid as well as at high latitude locations. Whereas at Kwajelin variation of NmF2 is maximum during March and at Learmonth slab thickness is maximum during June and September.

Diurnal variation of NmF2 and slab thickness (τ) during quiet days and disturbed days:

Figure 7 and 8 represents the diurnal variation of NmF2 and τ for magnetically quiet and disturbed days. It is seen from the figures that NmF2 and τ is maximum during day time hours at different latitudes. The effect of magnetic disturbances on the average diurnal variation does not show any dependence at all the locations.

Seasonal variation of NmF2 and slab thickness (τ) during quiet days and disturbed days:

Figure 9 and 10 represents the mean diurnal variation of NmF2 and slab thickness during winter, summer and equinox months. It is seen that at Chilton NmF2 shows a sharp day time minimum and a broad day time maximum during winter months, whereas during same period of time, slab thickness shows a peak during sunrise hours. During summer months NmF2 is maximum at sunset hours while slab thickness was maximum during day time. At mid latitude and low latitude locations NmF2 and τ show a sharp day time maximum for all the seasons. The effect of magnetic disturbances on the mean seasonal values at low, mid and high latitude location is not clearly noticed.

DISCUSSION

The topside ionosphere is mainly composed of ions O+, H+ and He+. The abundances of these ions are dominated by transport and chemical processes (Chandra and Rangaswamy, 1976; West et al., 1997; Zaho et al., 2005). The plasma distribution of the equatorial and mid-latitude ionosphere is subject to a number of transport processes involving thermospheric neutral winds, EXB drifts, and field-aligned diffusions (Venkatraman and Heelis, 2000). Torr and Torr (1973) reported that the winter anomaly is due to an increase in the [O]/ [N2] ratio caused by the convection of atomic oxygen from the summer to winter hemisphere. This is supported by the fact that [O]/[N2] ratio is 2-3 times larger in winter than in summer (Cox and Evans, 1970). A summer to winter trans-equatorial wind produces an increased peak density and hence the larger winter values are reported (Titheridge and Busantano 1983; Rishbeth et al., 2000). The lower value of IEC during summer months may be attributed to the low ionization densities, due to the reduced production rate (indicated by O/N2 ratio); owing to the increased scale height of N2 (Titheridge, 1974). Our results for low latitude are in good agreement with those reported (Bhuyan et al., 1992 and Huang et al.,

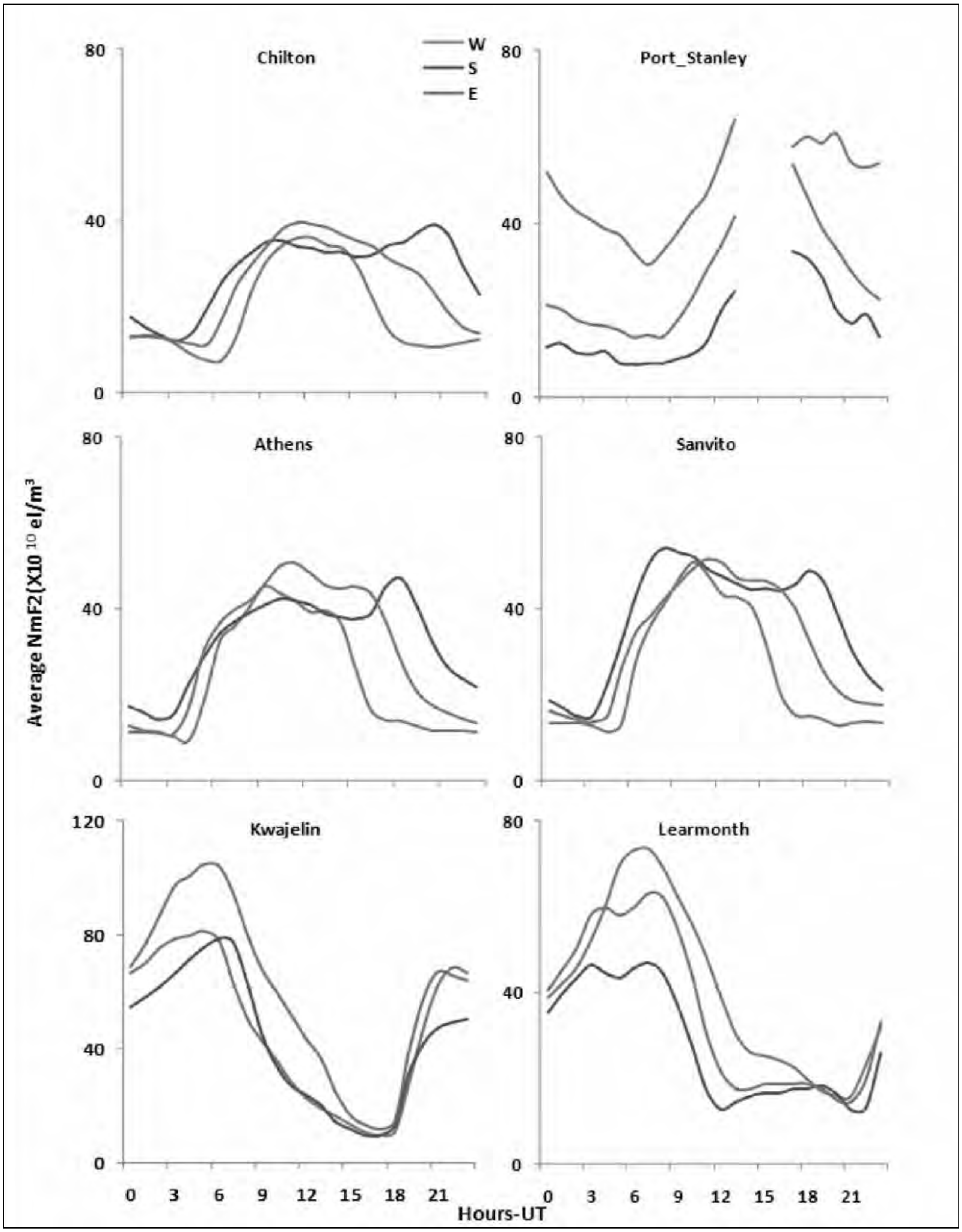

Figure 3. Seasonal variation of NmF2

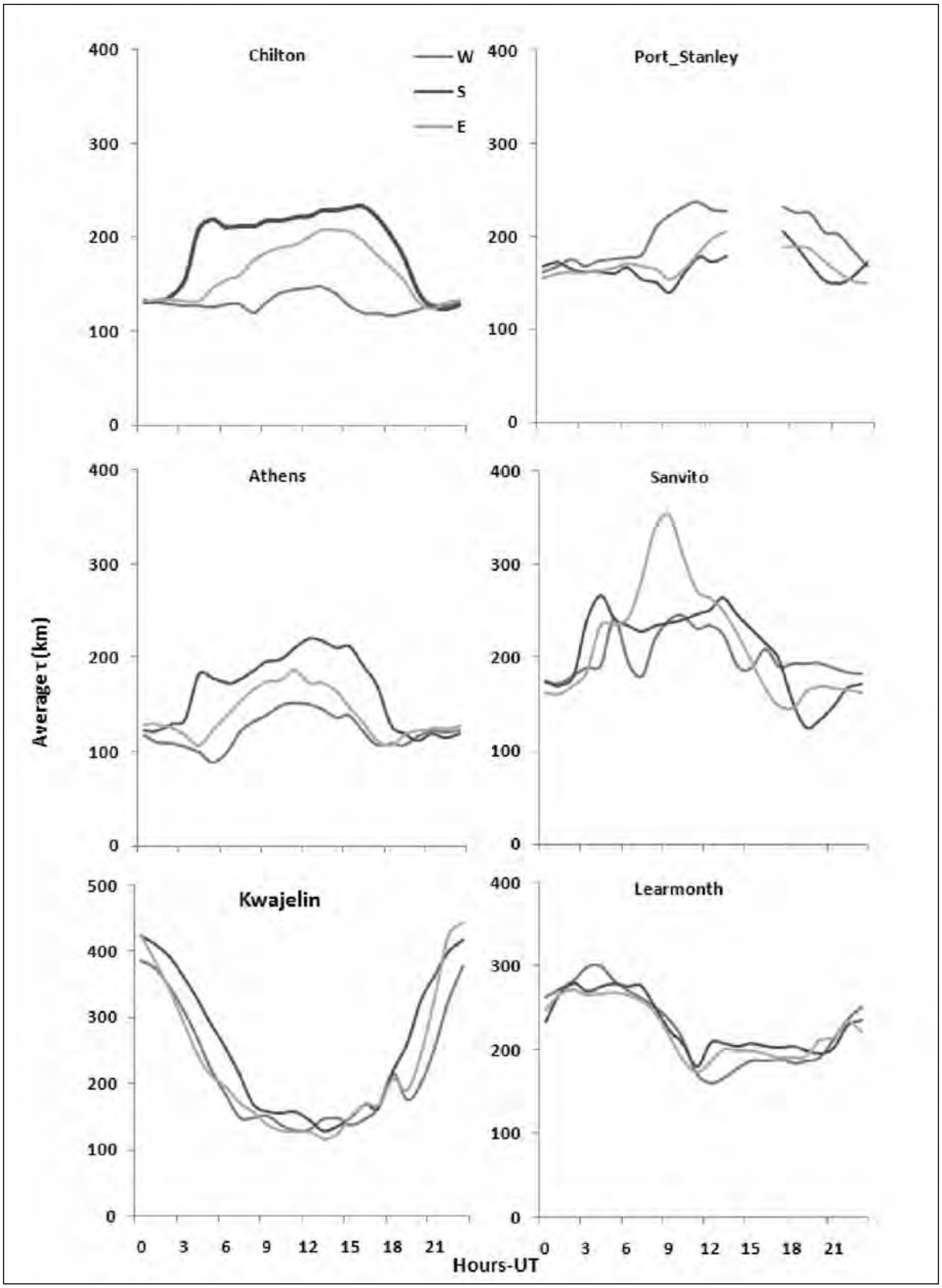

Figure 4. Seasonal variation of TAU(Km)

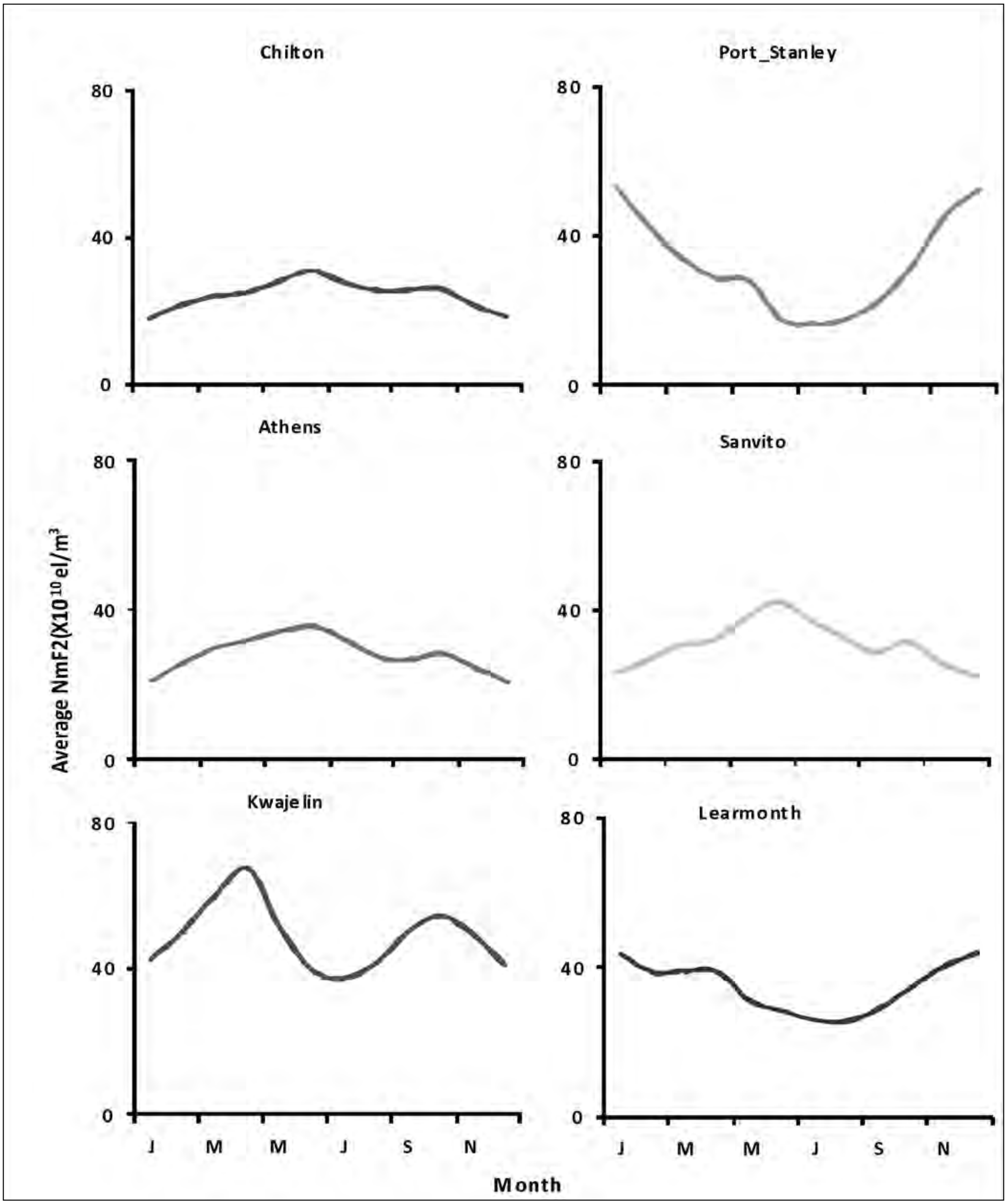

Figure 5. Monthly variation of NmF2

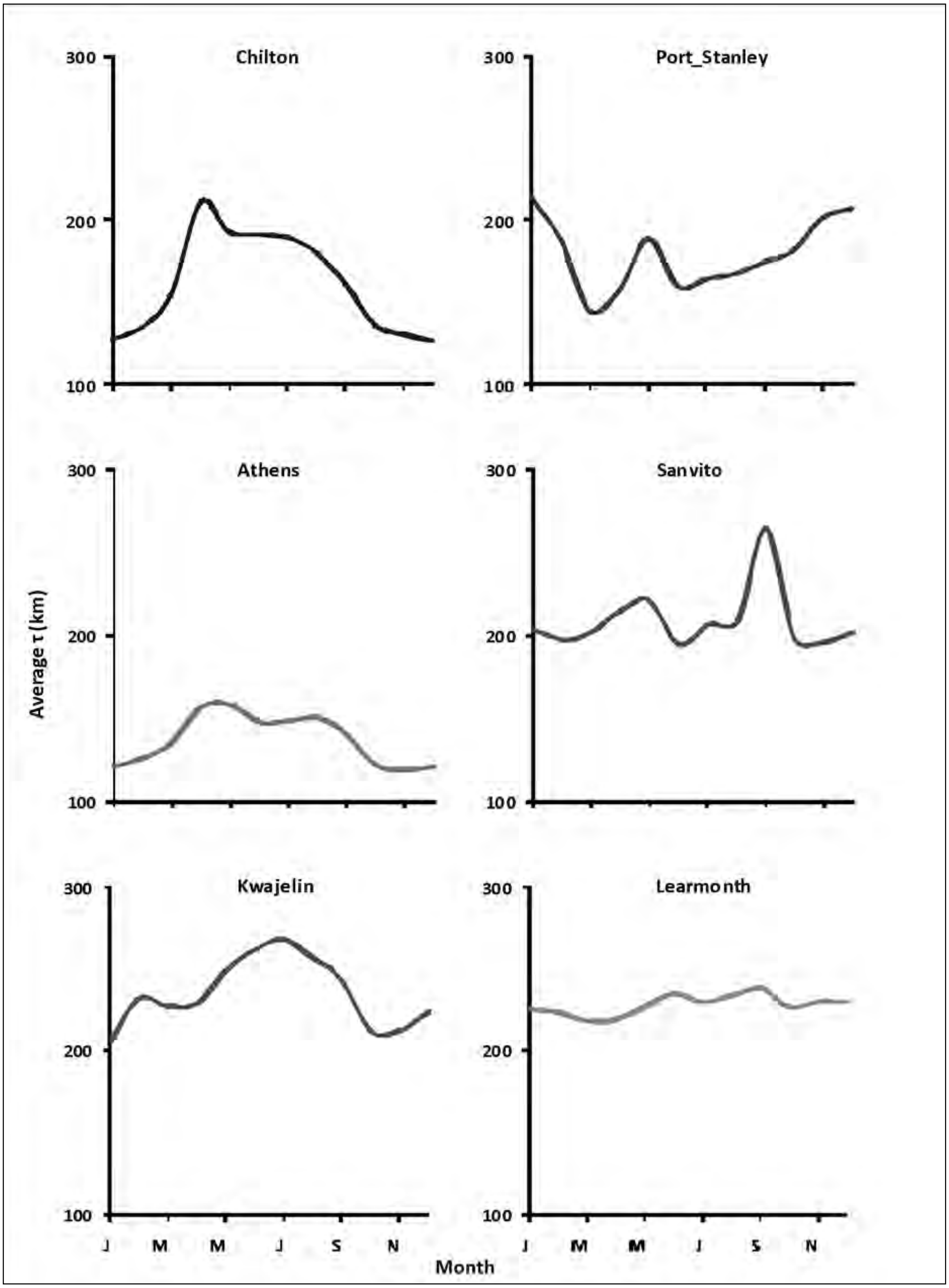

Figure 6. Monthly variation of TAU (km)

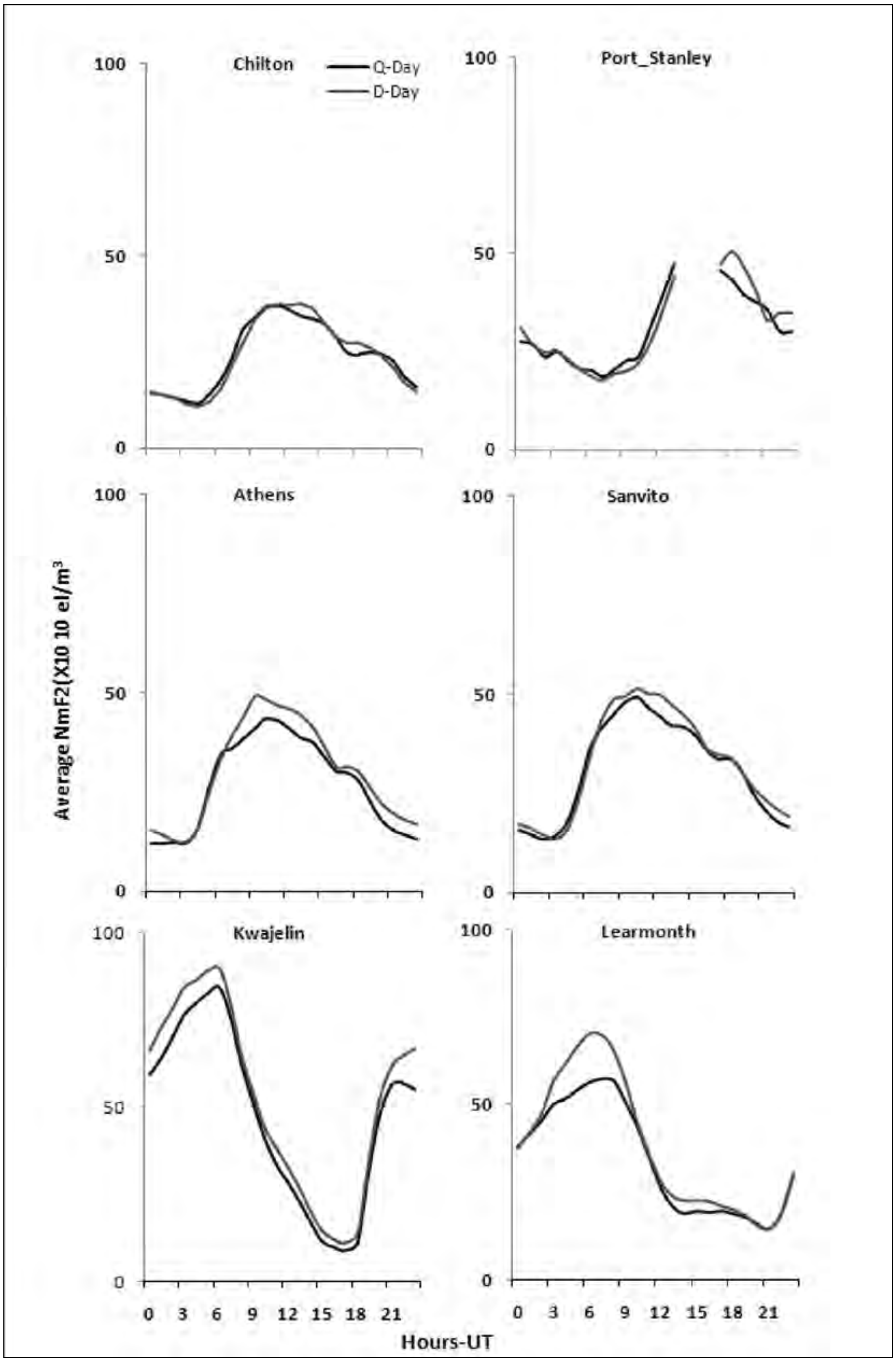

Figure 7. Diurnal variation of NmF2 during quiet and disturbed days

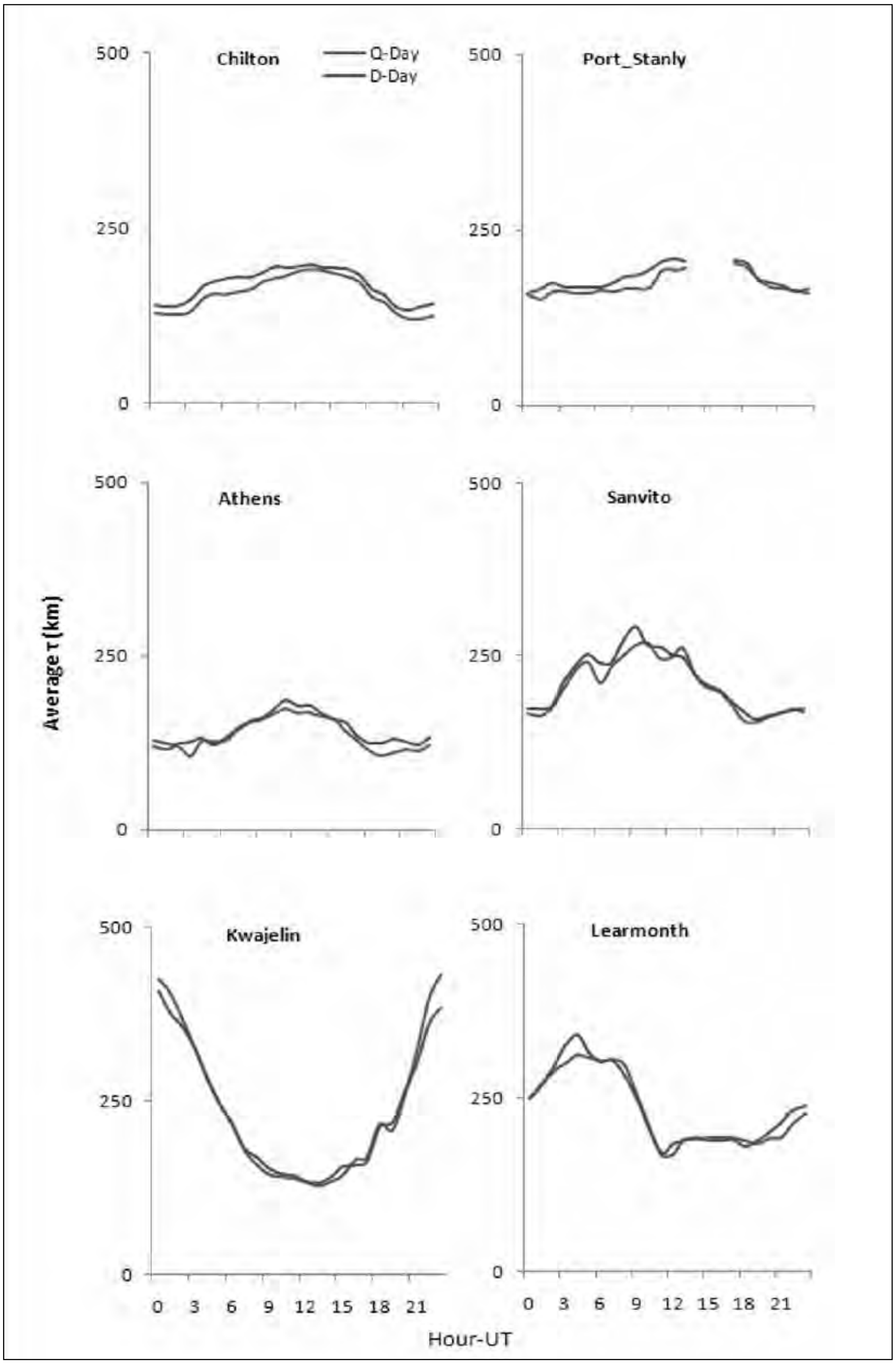

Figure 8. Diurnal variation of TAU during quite and disturbed days

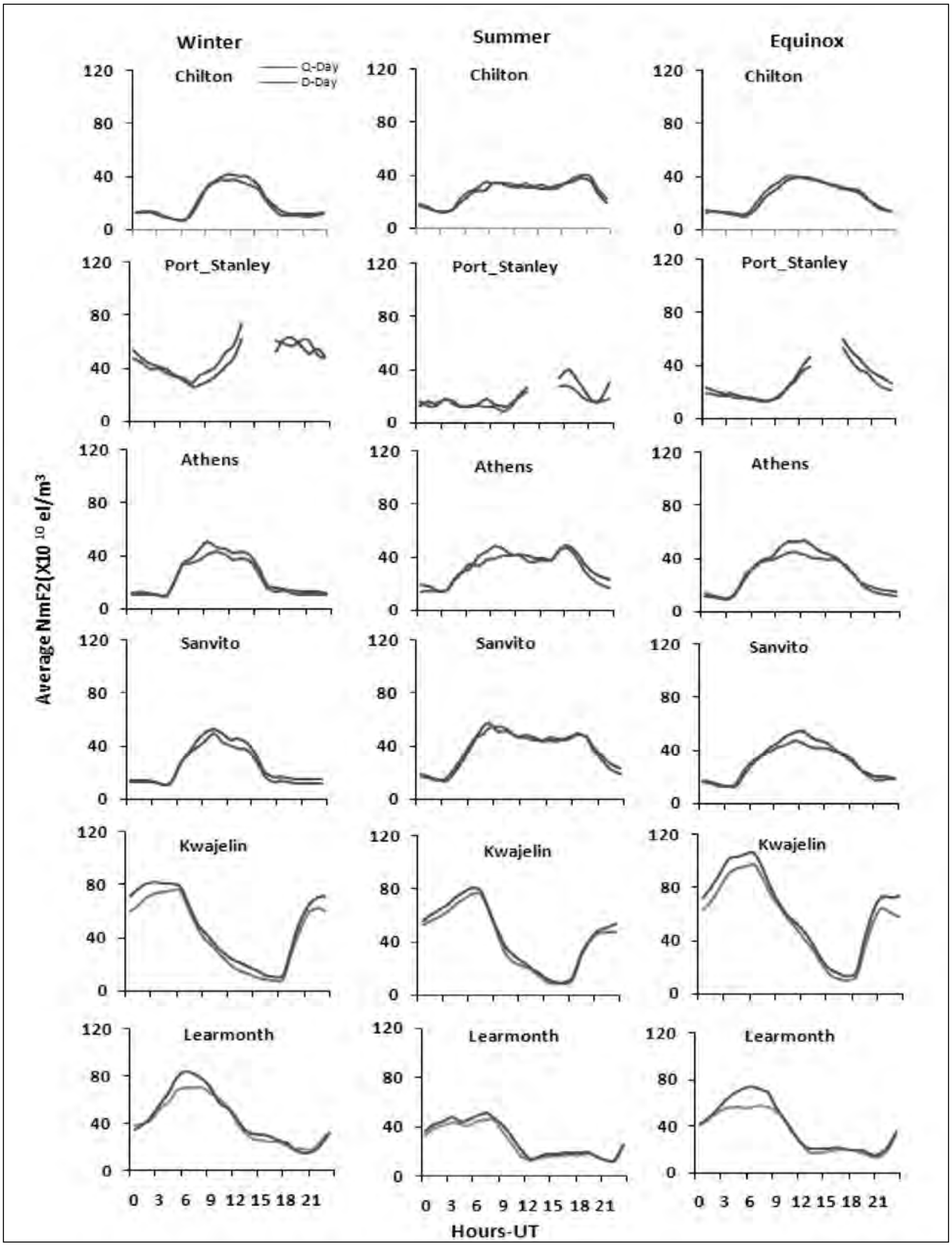

Figure 9. Seasonal variation of NmF2 during quiet and disturbed days

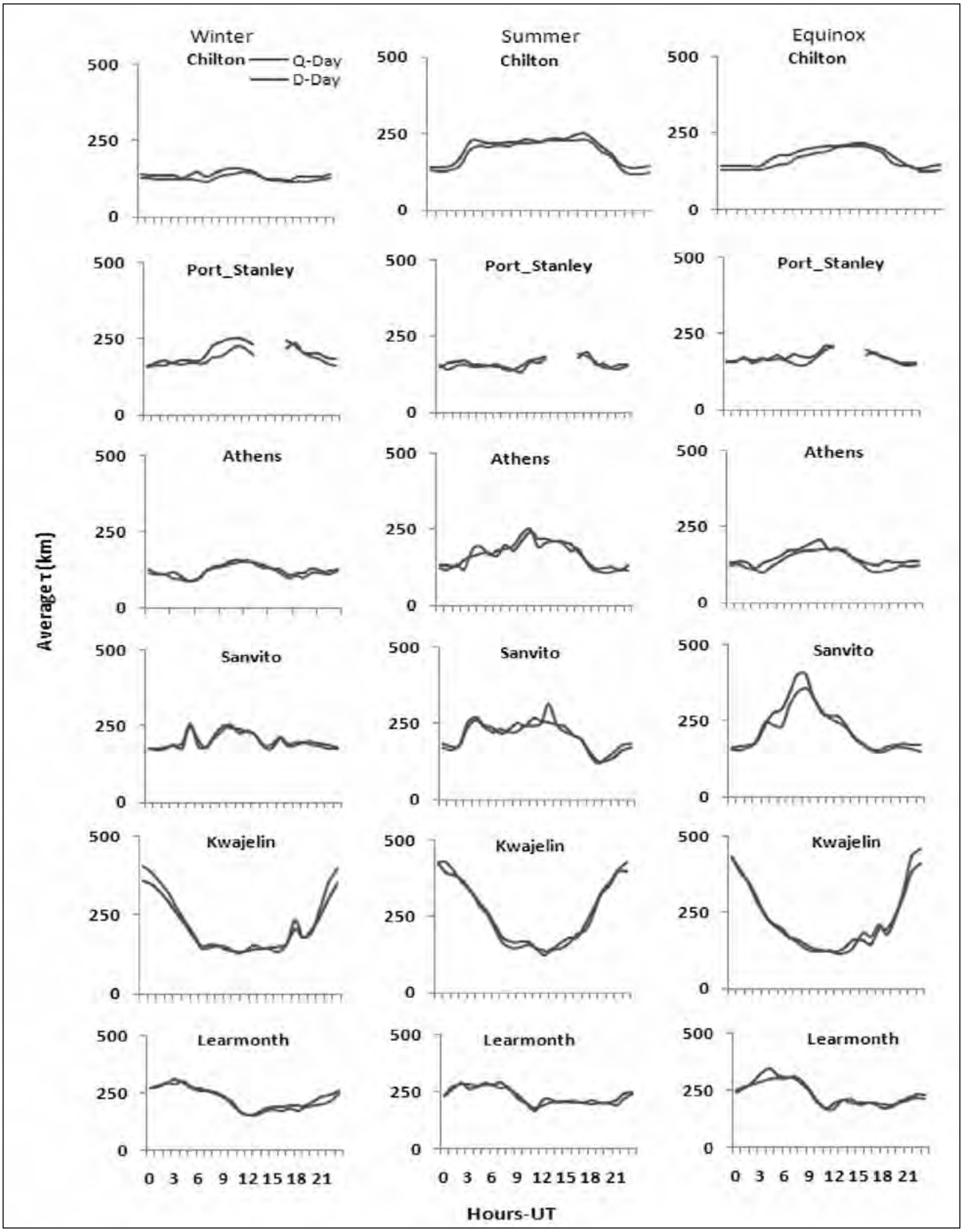

Figure 10. Seasonal variation of TAU during quiet and disturbed days

1995). Higher variability of IEC is observed in winter than in summer from IEC data of Lunping (25^0N, 191.3^0E). For descending phase the short-term as well as long term variations of IEC, within and near the crest of equatorial belt, are mainly controlled by the equatorial and electrojet strengths.

The seasonal anomaly variation of the thermospheric neutral composition has been suggested to be the major source of the winter anomaly (Rishbeth and Setty, 1961; Duncan, 1969; Lamb and Setty, 1976; Balan et al., 1998; Rishbeth, 1998; Rishbeth and Muller-Wodrag, 1999, 2006, Rishbeth et al., 2000, 2004; Yu et al., 2004). Upwelling of the atmosphere in summer, dowelling in winter and summer to winter wind circulation induce different thermospheric neutral compositions between summer and winter. In summer increase in molecular gas in the F region, owing to upwelling, enhances the reaction of O+ with molecular gases, resulting in a plasma density decrease. The opposite process occurs in winter, resulting in a plasma density increase. The seasonal variation in the number density of the vibrationally excited molecular gases (N_2 and O_2) and electronically excited O+ also contributes to the generation of the winter anomaly (Thomas, 1968; Strobel and McElroy, 1970; Torr et al., 1980; Pavlov and Pavlova, 2005). The production rate of vibrationally excited molecular gases, owing to collisions of unexcited N_2 and O_2 with thermal electron, increases with an increase in electron temperature (Pavlov, 1998). Because the electron temperature is higher in summer than in winter, the number density of vibrationally excited molecular gases in summer exceeds that in winter. Both the neutral composition and the population of vibrationally excited molecular gases vary with solar cycle, and therefore, the intensity of the winter anomaly is dependent on the solar cycles. The seasonal change in neutral composition has been identified by ground based radar and satellite observations (Alcayde et al., 1974; Hedin and Alcayde, 1974; Mendillo et al., 2005). The contribution of the vibrationally excited molecular gases to the F-layer winter anomaly is 20% -40% (Torr et al., 1980; Pavlov and Pavlov, 2005). This rate decreases with solar activity (Pavlov and Pavlova, 2009).

The winter anomaly has been investigated using NmF2 values observed from ground ionosondes (Yonezawa, 1971; Torr and Torr, 1973; Zou et al., 2000; Yu et al., 2004; Pavlov and Pavlova, 2009, Pavlov et al., 2010). Torr and Torr (1973) provided the global map of the winter anomaly using NmF2 data from world wide ionosonde stations. Their results show that the winter anomaly is more pronounced during the solar maximum period and in the Northern Hemisphere. The results of Pavlov and Pavlov (2009) could not determine the intensity of the winter anomaly accurately as they have not exclude the data pertaining to the magnetically disturbed periods. However, the TEC derived from the Ocean Topography Experiment (TOPEX) satellite shows similar hemispheric and solar cycle dependence of the winter anomaly during the magnetically quiet condition (Jee et al., 2004).

The existence of a pre-dawn peak in equivalent slab-thickness has been reported earlier by many workers (Rastogi et al., 1979; Sethia et al., 1980, Bhuyan et al., 1986; Prasad et al., 1987; Davies and Liu 1991; Jayachandrnan et al., 2004 and Chou, 2007). The morning peak in slab thickness was attributed to the rapid ionization of the topside ionosphere, which increases the TEC while the peak electron density (NmF2) was lagging behind. Titheridge (1973) suggested that the pre-sunrise peak in τ is due to the downward movement of the ionosphere. Large values of equivalent slab thickness during pre-dawn hours may also be attributed due to the fact that a significant portion of electrons in TEC are associated with H+ ions, which have large scale heights (Sethia et al., 1980). Soon after the occurrence of the morning peak, the slab thickness decreases to a small value indicating a rapid production of ionization around the peak of F2-layer. The atmospheric neutral winds and enhanced eastward electric field have significant and dominant influence on the peaks during these two periods (Chou et al., 2010).

The post-sunset increase in the τ value during the different seasons under varying solar activity conditions for low-latitude is due to the secondary fountain effect caused by the post-sunset occurrence of a strong eastward electric field existing over equatorial latitude is reported by Bhuyan (1986). The post-sunset enhancement in the τ values observed for the mid-latitude may also be associated with the night-time enhancement in ionospheric electron content at mid-latitude, which is primarily due to the field aligned plasma flow from protonosphere to ionosphere (Minakoshi and Nishimutha, 1994). Our result show that the value of slab thickness is high during daytime hours, which is in good agreement with the result of Mahajan et al., (1968). The high value of slab thickness during day time is consistent with electrodynamic drift (fountain effect), which enhances the content of topside. The decrease in slab thickness after 2200 hours may be caused by the movement of the equatorial ionosphere to lower altitudes around this time. Balsley and Woodman (1969) reported that the vertical drift velocity at the magnetic equator is highly correlated to the strength of electrojet current. As a result, the characteristics of the equatorial anomaly should be closely related to the strength of the electrojet current. This has been shown by several workers (Dunford, 1967, 1970; Walker and Ma, 1972, Rush and Richmond 1973). The latitudinal gradient of slab thickness, being primarily governed by vertical drift velocity at the magnetic equator, should increase with the strength of the electrojet current. Das Gupta (1975) using the ionospheric electron content and equivalent slab thickness in the equatorial region around 750E, found that slab thickness exhibits a strong latitudinal dependence with a maximum at the magnetic equator and a minimum around the crest of the F2 anomaly. This inturn suggests that the F-region is thick near the equator and most skewed near the crest. This is attributed due to the electrodynamics drift and diffusion in the equatorial ionosphere. Around noon, when the electrodynamic force attains its maximum value, the altitude of the field-aligned ionization arch becomes maximum at about 800 km over the magnetic equator, and the crest of the equatorial F2 anomaly moves farthest apart. In the late afternoon the process is reversed, and the crest comes closer, merging finally into a single crest at the magnetic equator. Since the above geomagnetic control is a feature of considerable height range in the top side ionosphere, the ionospheric electron content IEC, which is heavily weighted by ionization up to about 600 km, is expected to exhibit a latitude variation similar to the equatorial anomaly in F2 ionization

Busantano et al., (1979) made a comparative study of the variation of τ for mid-latitude station at Sagamore Hill and the high latitude station at Goosebay during the low, medium and high solar activity periods of the 20 solar cycles. They observed many similarities in the variations of τ for both locations. Most of the earlier studies on the influence of geomagnetic activity on the slab thickness were inconclusive. Bhuyan et al., (1986) reported no correlation between slab thickness and magnetic activity index Ap for Indian low latitude stations. Kersley and Hejeb (1976) report a positive correlation between ô and magnetic activity during medium solar activity conditions for the mid-latitude station Aberystwith (53^0N, 4^0W). Chuhan and Gurum (1981) report that during solar minimum period of 1975-76 for Indian low-latitudes. The increase and decrease of slab thickness occurs with equal frequency. They concluded that magnetic activity has no definite impact on slab thickness.

Rama Rao et al., (1985) reported the direct control of solar activity on the ionization level, with higher values during a high solar activity period. During the period of a low sunspot number, the IEC builds up quite slowly, resulting in a low value of day maximum. Many authors have reported positive dependence of slab thickness on S10.7 solar flux from various locations (Bhonsle et al., 1965; Dabas et al., 1984; Tyagi and Somayajulu, 1966). Davies and Liu (1991) studied the slab thickness in the low and mid-latitude and found its solar cycle dependence; they observed that the noon time slab thickness increases with increase of solar flux in all the seasons. They concluded that the predawn increase in slab thickness is caused by low values of NmF2, not by increase of IEC. Liu et al., (1992) report only a weak linear dependence of slab thickness with sunspot number. Jayachandran et al., (2004) concluded that solar activity dependence on τ indicates that it varies with latitude, season and also with levels of solar activity. Kersley and Hajeb Hossineieh (1976) reported a positive correlation between τ and magnetic activity during medium solar activity conditions. From our studies it is evident that the effect of magnetic disturbances on the average diurnal variations does not show any dependence at all the latitudes.

CONCLUSION

Present study on the diurnal, monthly, seasonal and latitudinal variations of NmF2 and slab thickness (τ) over six different locations Chilton, Port_Stanley, Athens, Sanvito, Kwajelin and Learmonth during low to moderate solar activity indicates a significant latitudanel variation in the equivalent slab thickness with higher daytime values over all the latitudes. The ionospheric monitoring capabilities of the slab thickness need to be explored. The maximum electron density of F2-layer (NmF2) at all the stations more or less show similar nature of variation with higher value during daytime as compares to those of slab thickness. The effect of magnetic activity disturbances on the average diurnal variation does not show any dependence on magnetic disturbances at all the locations. A brief review of the observations made by other researchers is presented to bring out discrepancies (in either the observations or their interpretation), most notably on issues such as the level of dependence on solar and geomagnetic activity, location, etc.

Since, continuous monitoring of slab thickness and NmF2 would help in various GNSS applications including improving the integrity and performance of network RTK positioning service and aircraft navigation, efforts should be made to strengthen research on ionospheric parameters and practical application of the derived models/results.

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