# Fourteen years of geomagnetic daily variation at Mario Zucchelli Station (Antarctica)

Santarelli L., Cafarella L., Lepidi S., Di Mauro D., Meloni A., Palangio P.
*Istituto Nazionale di Geofisica e Vulcanologia, Rome, Italy*

## Abstract

During the 1986-87 austral summer a geomagnetic observatory was installed at the Italian Antarctic Base Mario Zucchelli Station. In the first three years continuous time variation monitoring and absolute measurements of the geomagnetic field were carried out only during summer expeditions. Starting 1991 an automatic acquisition system, operating through all the year, was put in operation. We present here some peculiarities of the daily variation as observed for fourteen years (1987-2000). The availability of a long series of data has allowed the definition of seasonal, as well as solar cycle effects, on short time variations as observed at a cusp-cap observatory. In particular, contrary to mid latitude behaviour, a clear dependence of the daily variation amplitude on the global geomagnetic $K_p$ index was well defined.

*Key words* – geomagnetic daily variation, polar areas.

## Introduction

It is well known that the interaction of the variable solar wind with the magnetosphere is the main cause of the magnetospheric dynamics and of some special geophysical phenomena such as auroral emission (e.g. Russell, 1986; Carlson and Egeland, 1996). The study of upper atmosphere and magnetosphere phenomena in the polar regions is very important because of the direct connection of polar geomagnetic field lines to the solar wind through the magnetopause and the magnetospheric tail regions.

The ground measurements of magnetic field fluctuations in the polar regions are an important tool of investigation for plasma processes (e.g. Lanzerotti et al., 1994; Villante et al., 1997 and the references therein). Important roles, in the generation of magnetic variation, with periods ranging from few seconds to tens of minutes, are played by the incidence of hydromagnetic waves and of density oscillations of the solar wind, the Kelvin Helmholtz instability on the magnetopause, the interaction with interplanetary shocks, field aligned currents and radiation belt charged particles falling from the magnetosphere onto the upper ionized atmosphere. For longer periods, changes in solar ultra-violet or X-ray fluxes likely play a major role (Nishida and Kokubun, 1971). In particular, the daily variation (24-hour period and its harmonics), is generated in the polar cap by two different ionospheric current systems: $S_q^0$ (the extrapolation of the mid latitude $S_q$ system driven by the ionospheric dynamo) and the polar cap system $S^p{}_q$ generated by external sources related to processes in the magnetosphere and its interaction with the Interplanetary Magnetic Field (IMF) (e.g. Nagata and Kokubun, 1962; Ractliffe, 1972; Brekke, 1997). The $S_q^p$ system is believed to be the primary source for the daily variations, especially during local winter when the southern polar cap is not exposed to solar illumination (e. g. , Akasofu et al., 1983; Brekke, 1997).

The Antarctic observatory at Mario Zucchelli Station (formerly Terra Nova Bay; the base name was changed in 2004; international geomagnetic observatory code TNB; geographic coordinates: 74.7°S, 164.1°E; corrected geomagnetic coordinates: 80.0°S, 307.7°E; LT=UT+13) is located in the polar cap. In this paper magnetic field data from 1987 to 2000 are analysed to investigate the influence of solar activity on daily variation and its distribution with respect to local time, season and solar activity.

## Measurements and data analysis

The location of Mario Zucchelli Station, together with a statistical pattern of auroral power flux based on data from the Total Energy Detector (TED) on board the NOAA-16 satellite (courtesy of the U.S. Departement of Commerce, NOAA, Space Environment Center) over Antarctica, is shown in Figure 1; the local time at TNB is LT=03. During periods of average magnetic activity, the station is inside the polar cap quite close to the auroral oval. Under particular geomagnetic conditions and for a particular range of LT's it could be situated under the southern polar cusp, and thus the geomagnetic variations in this condition could be heavily influenced by local cusp phenomena, mainly related to field-aligned currents (Matsushita and Xu, 1982; Campbell, 1997).

Variations in the Earth's magnetic field were measured by means of three-axis fluxgate magnetometers located at TNB (Meloni et al., 1997). The variations are measured along three directions oriented respectively with reference to the local magnetic meridian: the horizontal magnetic field intensity H-component (south-north), the orthogonal-component D in the horizontal plane (west-east, then D is an intensive element, expressed consequently in nT, and not the angular element declination) and the vertical intensity Z-component (consequently positive increase inward). We used hourly means for D, H and Z after subtracting daily mean values.

Summaries of the hourly mean values of the deviation from the average of the Earth's magnetic field H- and D-components for one year (1993, chosen since it has a good data coverage) are shown in Figure 2 as statistical box-plots. For each magnetic element, the hourly average values in 5-day intervals were statistically sorted and binned according to their magnitudes; the centre 50% of the data in each interval is contained in the individual boxes (e.g. Kleiner and Graedel, 1980). Because of the removal of the mean values, the median value tends generally to be close to zero; in each interval the median value is given by an horizontal line across a box. The upper (lower) 25% of the distributions lies within the ranges given by the lines extending up (down) from the individual boxes.

The mean daily variations at TNB observatory during years 1991 and 1996, one at the maximum and one at the minimum of solar activity, are shown in Figure 3 as box-plot statistics organised as a function of universal time (UT) for three seasons selected according to the Lloyd criteria (Lloyd, 1861): summer (Nov, Dec, Jan and Feb, left panels in the figure); equinoxes (Mar, Apr, Sep. and Oct center panels); winter (May, Jun, Jul and Aug, right panels). The plots were obtained by superimposing one day on top of another. In this way a single box represents the variations at each UT hour for the whole period considered.

Figures 4 a, b, and c show magnetic field hodograms in the horizontal plane sorted by local season (summer, upper panel; equinoxes center panel, winter, lowest panel) respectively, from 1987 to 2000. The D and H median values (one value for each hour) are plotted on the X and Y axis, respectively. The 24 values represent the dynamics through the day of the projection of the total field F on the horizontal plane.

## Discussion

Some general information about solar cycle 22 and 23 can be useful in order to better introduce some features that can be observed in the figures mentioned above.

Solar cycle 22 is one of the largest amplitude sunspot number cycle ever recorded, continuing the sequence of strong cycles which includes cycle 19 and cycle 21. Solar cycle 22 started at the end of 1986 and reached its maximum phase in 1991; then it declined in early 1992 (sunspot number passes from a value of more than 150 at the end of 1991 to less than 100 in 1992). The lowest number of sunspot cycle 22 was officially recorded in May 1996, only after 9.8 years from its beginning. The maximum phase brought some extraordinary intervals of activity. In particular, June 1991 produced the most outstanding solar flare activity of this cycle. In the interval June 1st to June 17th numerous intense solar flares were recorded. Cycle 23 started in May 1996 with the monthly sunspot number at 8.0 and peaked in April 2000 at 120.8.

The 1993 TNB box-plot statistics in Figure 2 (shown as an example) exhibits a very clear seasonal effect in both D and H components (Cafarella et al., 1995; Cafarella et al. 1998). The magnetic fluctuation level is considerably larger during local austral summer than in austral winter. This feature can be explaned in term of the increase in ionospheric ionization, and then in electrical current intensities, produced by solar em waves irradiation in summer season. There are some exceptions, corresponding to intervals of significant geomagnetic activity during local winter; for example in May 1993 (days 130-134) when the total range of differences in the 5-day bin is comparable to that seen during austral summer conditions. This increase in the range of magnetic variations during periods of high geomagnetic activity should arise from charged particle ionisation in the ionosphere, as well as the intense field-aligned and ionospheric currents which are present in the auroral regions expecially during open magnetospheric conditions (Campbell, 1997).

Additional information on the daily variation can be obtained by examining the magnetic fluctuations at the station as a function of solar activity, local time and season. In figure 3 mean daily variation as box-plot statistics as a function of UT for two different years (max and min solar activity, 1991 and 1996 respectively) is reported. It is clear from the plots that the pattern of diurnal variation, in all the components, does not depend on the season nor the solar activity: in particular, independently on season and solar activity the H component reaches maximum values in the UT afternoon, while the D (Z) component shows a broad minimum (maximum) around UT noon. Conversely, the variation amplitude strongly depends both on season and solar activity. In general smaller local time variations during austral winter (as would be expected from Figure 2) can be observed with respect to summer (Figure 3). In any case the most important role determining the variation amplitude is played by the solar cycle: indeed 1991 winter variations are even larger than 1996 summer variations. Some peculiarities are evident in both cases: the largest dispersion with respect to the median values occurs in the southern summer and the smallest during the winter. In particular, during summer the largest D day-to-day variations are just before UT midnight and the smallest ones are in early morning and in afternoon. The situation is quite different for the H-component: the largest variations during summer are in UT evening and in the UT early morning, and the smallest variations are just after UT noon, indipendently from solar activity. Almost the same situation can be observed during the equinoxes (central panels) and in local winter, exept for a shift of the H component smallest variation at about before UT noon.

The vertical Z component amplitude variation does not show a definite UT dependence.

New information on daily variation under different solar activity can be obtained by means of hodograms. The hodograms shown in figure 4 correspond to local summers, equinoxes and winters, from top to bottom respectively. Each data point corresponds to the same hour averaged over the season. The amplitudes of the excursions over 24 hours are shown to be directly dependent on solar activity. The largest excursions occurred in 1989 summer followed respectively (on the same plot) by 1992 and 1991 (almost with the same amplitude) and 1999 and 1994. The smallest excursions occurred, for local summers, in 1997, followed by 1996, 1995 and 1987. For the equinoxes largest amplitude is for 1991 followed by 1992, 1993, 1994 and 1999 while the smallest ones are in 1997, 1996 and 1995. In winter the situation is quite different: largest excursions were in 1991 followed by 1994, 2000; the smallest ones were in 1997, 1996 and 1995.

Sunspot number, $K_p$ index and average excursion of the daily variation for the H, D and Z elements for the three seasons are reported in figures 5a, 5b and 5c. In each panel the median daily range (peak to peak) is reported for every year. As is clear from the plots, the strong activity during 1991 is evident, looking at the H and D values for austral winter 1991. The values gradually decrease from the higher values corresponding to the peak of the cycle, to the lowest values, at the end of 1997, approximately one year after the minimum of the solar cycle, and then they grow up again with the new cycle 23. From the same figure it is also evident that the daily excursion amplitude is well related to the $K_p$ index. In Table 1 the correlation coefficient between H, D and Z daily excursions with the $K_p$ index is reported. The coefficients indicate a good correlation expecially between horizontal components and $K_p$ index. The correlation coefficient with the vertical component in summer and equinoxes is lower than the previous ones and this can be attributed to the influence of the induced electric currents on Z component: indeed during winter, when the ionospheric electric currents intensity is lowest, the correlation coefficient with the vertical component is comparable with the other components.

| | **H and $K_p$ index** | **D and $K_p$ index** | **Z and $K_p$ index** |
|---|---|---|---|
| **Local summer** | *0.83* | *0.84* | *0.70* |
| **Local equinoxes** | *0.91* | *0.90* | *0.53* |

| | | | |
|---|---|---|---|
| **Local winter** | *0.95* | *0.94* | *0.94* |

Table 1: Correlation coefficient between H, D and Z daily excursions with the $K_p$ index.

## Conclusions

Monitoring of electromagnetic geophysical parameters in polar areas is fundamental in many fields since it can give important information for a better comprehension of the Earth's magnetosphere structure and evolution, and the solar control on magnetic activity as observed at Earth’s surface.

The diurnal variation of geomagnetic field elements is a well known phenomenon that has been extensively studied especially at mid latitudes. An equivalent electric current system is often used to represent the source of the observed field. At middle latitudes the equivalent current system consists of two current vortices, centred at about 40° latitude N and S respectively. A special additional contribution to diurnal variation appeared necessary in order to justify the polar daily variation plots. This additional field was called $S^d_q$ (Solar quiet polar) or $DP_2$ according to various authors ([Nishida and Kokubun, 1971]; Ratcliffe, 1972]). A possible cause of the polar current system is the magnetospheric convection that generates a quasi permanent current system in the polar regions which is steadily oriented with respect to the Sun-Earth line; the Earth rotation underneath this system causes the magnetic field elements daily variation.

Our analysis, based on box-plot statistics, shows that the pattern of diurnal variation, in all the components, does not depend on the season nor the solar activity; conversely, the variation amplitude strongly depends on both season and solar activity. In fact, for each year a clear seasonal effect is visible, with largest variation during austral summer and middle and low activity during equinoxes and winter respectively. The dependence of the daily current system that causes the S field at the station on solar activity emerges, even more pronounced.

Looking at the plots, a link between some characteristic of daily variation and magnetic activity was immediately evident: when the planetary magnetic activity is higher the variation amplitudes in all seasons are higher. We can conclude that, at high latitude, contrary to what happens at middle latitude, daily variation depends strongly also on magnetic global activity. This result is consistent with previous findings (Lepidi et al., 2003), obtained from the analysis of a very short data set (approximately 1 month) during local summer at cap latitudes.

## Figure captions

**Figure 1**: Geographical location of Mario Zucchelli Station (TNB) magnetic observatory in Antarctica. A statistical pattern of auroral power flux based on data from the Total Energy Detector (TED) on board the NOAA-16 satellite (courtesy of the U.S. Departement of Commerce, NOAA, Space Environment Center) is also reported. The red arrow indicates the magnetic local noon.

**Figure 2**: Hourly horizontal magnetic field intensities shown as box-plot statistics binned in 5-day intervals for the year 1993.

**Figure 3**: TNB box plots values of hourly means organised as a function of local time for three seasons in 1991 (high magnetic activity) and 1996 (low magnetic activity). Results are given for the magnetic field elements, H, D, and Z.

**Figure 4**: Hodograms (H vs D) for observatory values for local summer (a), equinoxes (b) and winter (c).

**Figure 5:** Comparison among sunspot number, average $K_p$ index and daily variation excursion of H, D and Z component for local summer, equinoxes and local winter respectively.

## References

AKASOFU, S. I., B. H. AHN AND G. J. ROMICK (1983): A study of the polar current system using the IMS meridian chains of magnetometers, Space Sci. Rev., 36, 337-413.

ARMADILLO, E., TABELLARIO G., BOZZO E., CANEVA G. (2003): Imaging the deep electrical conductivity structure of the rennik graben (north Victoria Land, Antarctica), Geophysical Research Abstracts, Vol. 5, 01171.

BREKKE, A. (1997): Physics of the upper polar atmosphere, John Wiley & Sons Ltd in association with Praxis Publishing Ltd, pp. 491.

CAFARELLA, L., A. MELONI, L.J. LANZEROTTI and C.G. MACLENNAN (1995): Small-scale variations in polar ionospheric electrical currents, Antarctic Journal of the United States, XXX, 5, pp. 347-349.

CAFARELLA, L., MELONI A. and PALANGIO P. (1998): Solar cycle 22 control on daily geomagnetic variation at Terra Nova Bay (Antartica), Annali di Geofisica, vol. 41, pp. 805-812.

CAMPBELL, W.H (1997): Introduction to geomagnetic fields, Cambridge University Press, 135-142.

CARLSON, H.C. and EGELAND A. (1996): The aurora and the auroral ionosphere, in Introduction to Space Physics, M. G. Kivelson and C.T. Russel Eds., Cambridge University Press, 568.

KLEINER, B. and GRAEDEL T. E. (1980): Exploratory data analysis in the geophysical sciences, Rev. Geophys. and Space Phys., Vol 18, pp. 699-717.

LANZEROTTI, L. J., L. V. MECLENNAN and L. V. MEDFORD (1994): Inferred quasi-steady ionospheric neutral winds and electrical currents at 79$^o$ south latitude in austral summer condition, Geoph. Res. Lett., 21, 217-220.

LEPIDI, S., L. CAFARELLA, P. FRANCIA, A. MELONI, P. PALANGIO and J.J. SCHOTT (2003): Low frequency geomagnetic field variations at Dome C (Antarctica), Ann. Geophys., vol 21, 923-932.

LLOYD H. (1861): On earth-currents, and their connexion with the diurnal changes of the horizontal magnetic needle. Trans. Roy. Irish Acad., 24, 115-141.

MATSUSHITA, S. and W. XU (1981): IMF sector effects on the polar geomagnetic field in winter, J. Geophys. Res., 86, 7143-7154.

MATSUSHITA, S and W. XU (1982): Equivalent ionospheric current system representing solar daily variations of the polar geomagnetic field, J. Geophys. Res, 87, 8241-8254.

MELONI, A., P. PALANGIO, L. CAFARELLA, G. ROMEO, E. BOZZO and G. CANEVA (1997): The Geomagnetic Observatory at Terra Nova Bay Base. Terra Antarctica, 1, 181-183.

NISHIDA, T. and S. KOKUBUN (1971): New polar magnetic disturbance: $S_p^q$, SP, DPC and DP2, Rev. Geophys. Space Phys., 9, 2, 417-425.

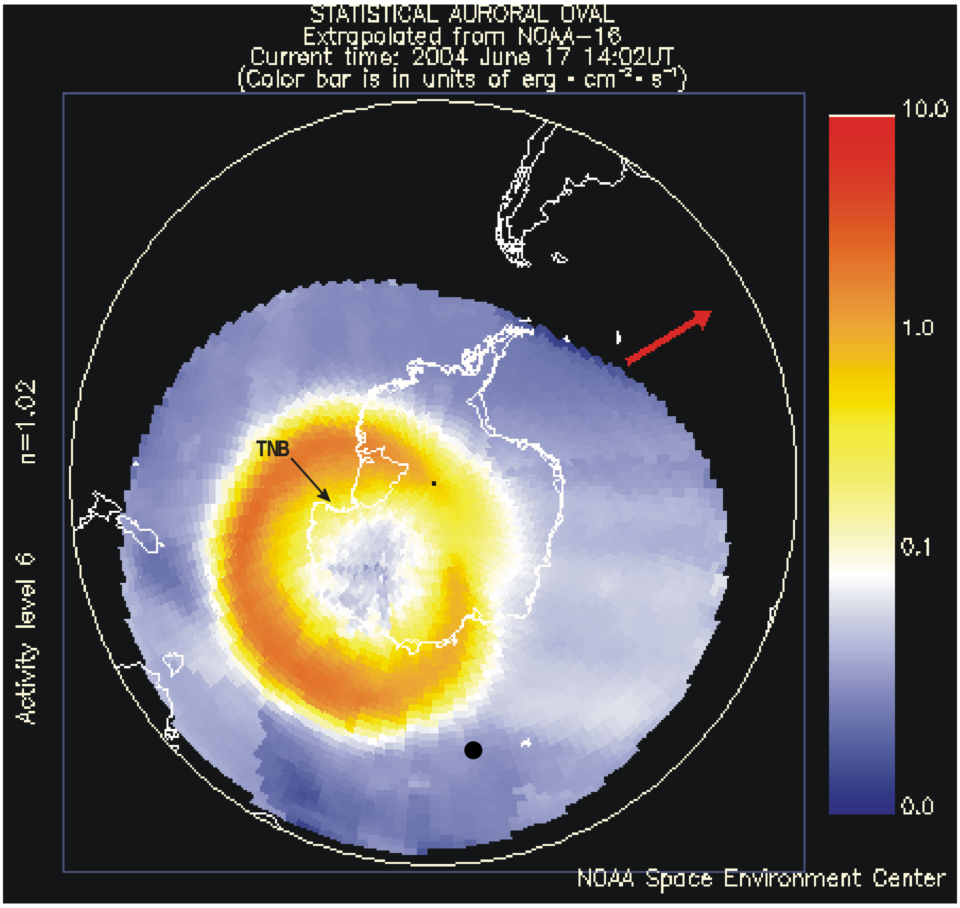
PAPITASHVILI, V. O., Y. I. FELDSTEIN, A. E. LEVITIN, B. A. BELOV, L. I. GROMOVA and M. VALCHUK (1990): Equivalent ionospheric currents above Antarctica during Austral summer, Antarctic Science, 2, 267-276.

RATCLIFFE, J. A. (1972): An introduction to the ionosphere and magnetosphere, Com. Uni Press, Cambridge, 256 pp.

RUSSELL, C. T. (1986): Solar wind control of magnetospheric configuration, in “Solar wind-magnetosphere coupling”, edited by Kamide and Slavin, Terrapub, Tokio, 209-231.

VILLANTE, U., S. LEPIDI, P. FRANCIA, A. MELONI and P. PALANGIO (1997): Long period geomagnetic field fluctuations at Terra Nova Bay (Antarctica), Geoph. Res. Lett., 24, 1443-1446.

Figure 1


STATISTICAL AURORAL OVAL
Extrapolated from NOAA-16
Current time: 2004 June 17 14:02UT
(Color bar is in units of erg · cm⁻² · s⁻¹)
Activity level 6
n=1.02
TNB
10.0
1.0
0.1
0.0
NOAA Space Environment Center

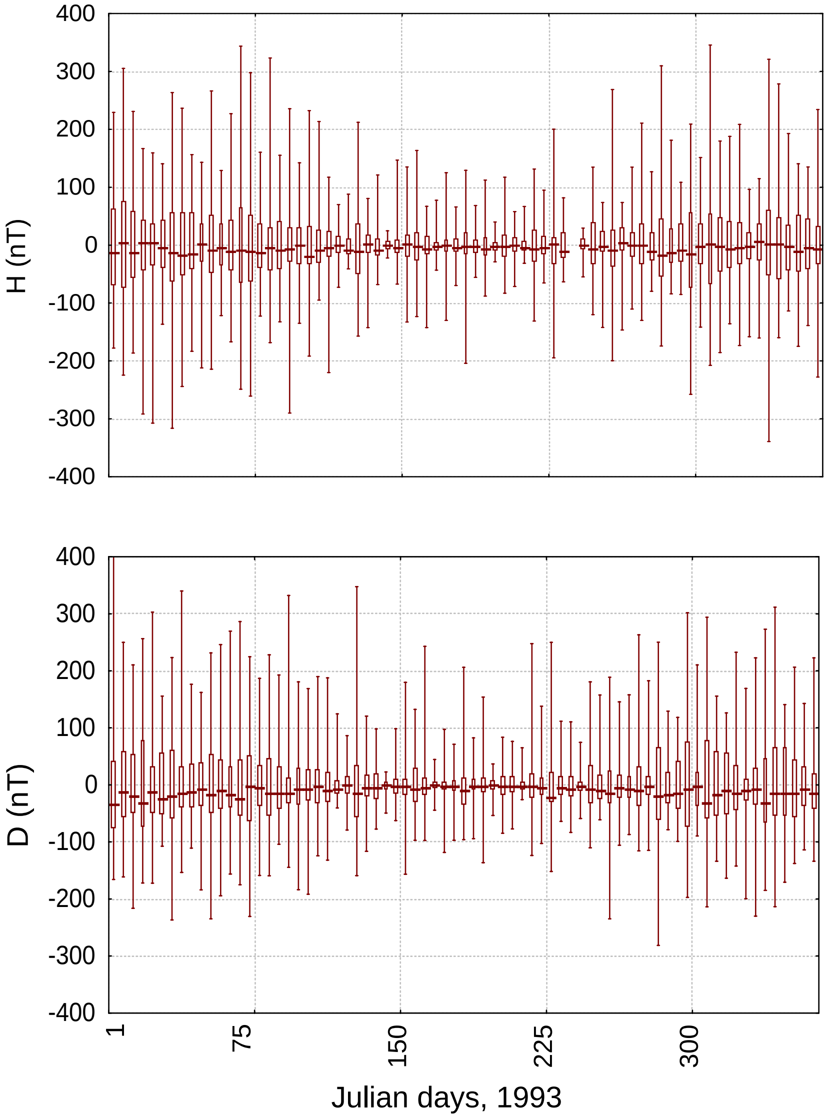
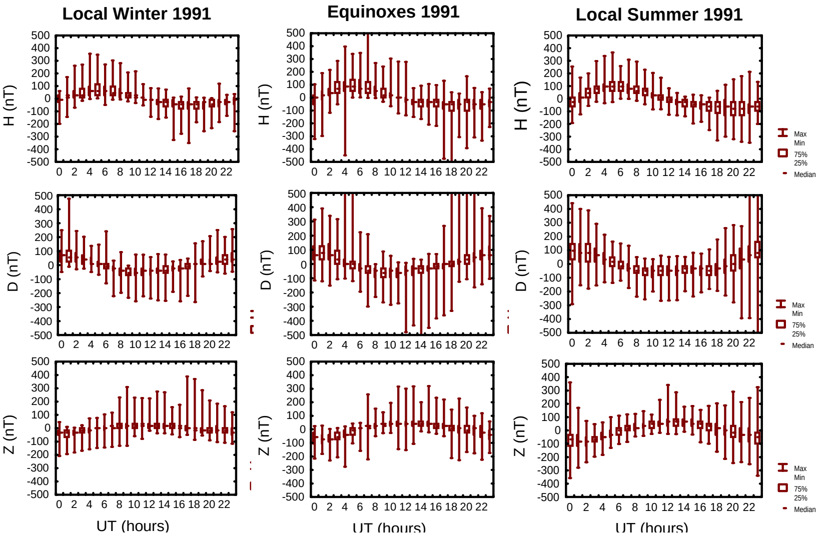
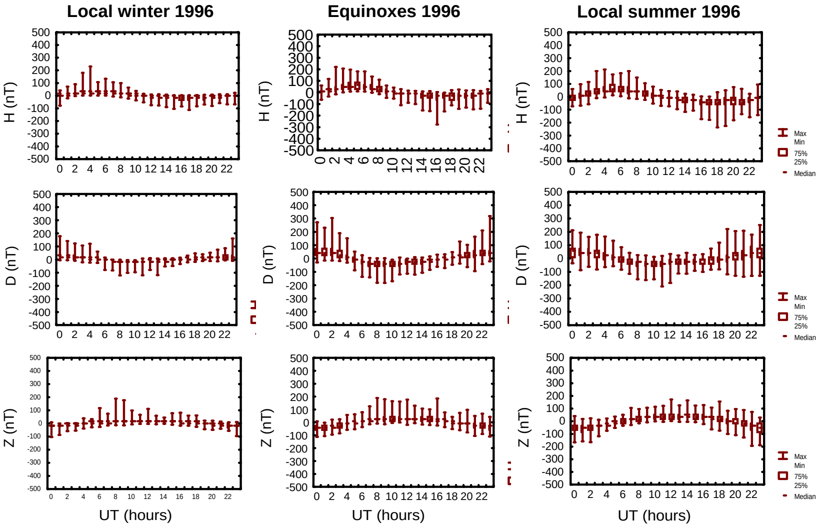

H (nT)
400
300
200
100
0
-100
-200
-300
-400
D (nT)
400
300
200
100
0
-100
-200
-300
-400
1
75
150
225
300
Julian days, 1993

Figure 2



a)

figure 3a



b)

figure 3b

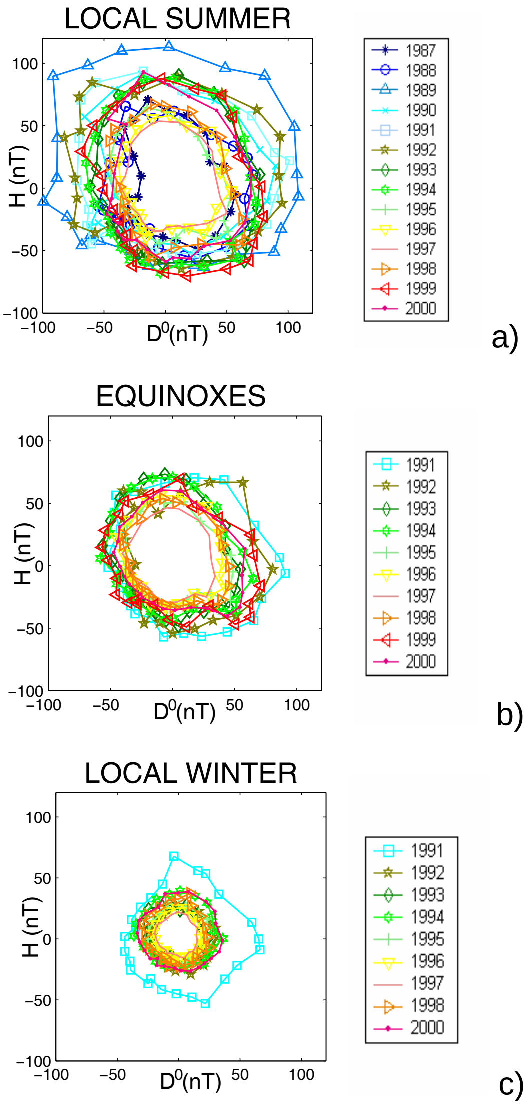
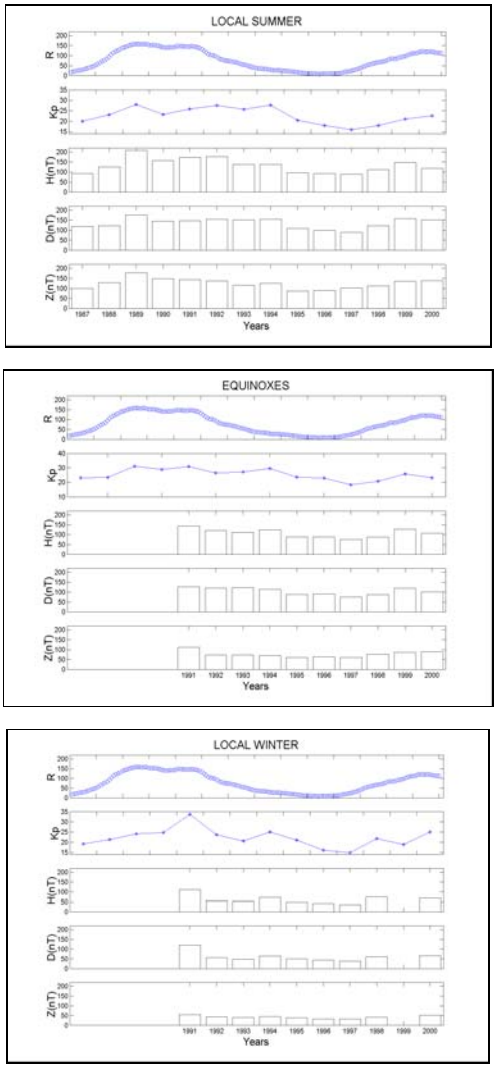

LOCAL SUMMER
H (nT)
D$^0$(nT)
100
50
0
−50
−100
−100
−50
50
100
1987
1988
1989
1990
1991
1992
1993
1994
1995
1996
1997
1998
1999
2000
a)
EQUINOXES
H (nT)
D$^0$(nT)
100
50
0
−50
−100
−100
−50
50
100
1991
1992
1993
1994
1995
1996
1997
1998
1999
2000
b)
LOCAL WINTER
H (nT)
D$^0$(nT)
100
50
0
−50
−100
−100
−50
50
100
1991
1992
1993
1994
1995
1996
1997
1998
2000
c)

figure 4

figure 5


LOCAL SUMMER
R
Kp
H(nT)
D(nT)
Z(nT)
1987
1988
1989
1990
1991
1992
1993
1994
1995
1996
1997
1998
1999
2000
Years
EQUINOXES
R
Kp
H(nT)
D(nT)
Z(nT)
1991
1992
1993
1994
1995
1996
1997
1998
1999
2000
Years
LOCAL WINTER
R
Kp
H(nT)
D(nT)
Z(nT)
1991
1992
1993
1994
1995
1996
1997
1998
1999
2000
Years