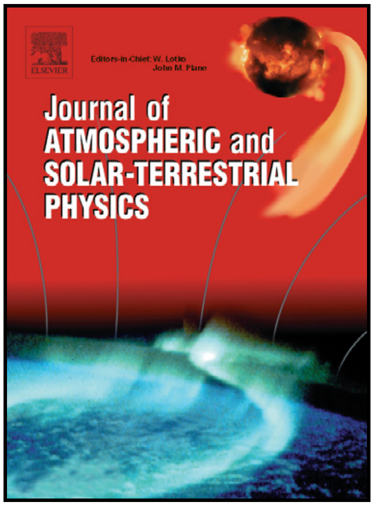

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ANALYSIS OF DAYTIME IONOSPHERE BEHAVIOR BETWEEN 2004 AND 2008 IN ANTARCTICA

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Abstract

In this paper we present 5-year study of the lower ionosphere behavior obtained from VLF sounding done at Comandante Ferraz Brazilian Antarctic Station. The results suggested a strong influence of 'meteorological processes' especially during wintertime, when VLF measurements showed that the D-region was strongly affected by planetary waves in all years. This effect was superposed to the well known control by solar radiation. The 16-day wave was the most important PW modulating the lower ionosphere behavior. Since planetary waves are very predominantly of tropospheric origin, this result is an evidence of the vertical couplings in the atmosphere-ionosphere system.

Keywords: ionosphere; VLF propagation; planetary waves; atmosphere coupling

1. Introduction

The lower ionosphere at heights between 60 and 100 km includes the diurnal D-region and the bottom of E-region. D-region has been probed by Very Low Frequency (VLF, 1 to 50 kHz) technique that monitors the VLF signals propagating over long distances in the Earth-ionosphere waveguide. The lower ionosphere perturbations are detected as amplitude and phase variations of the VLF signals. The VLF wave properties are described by the Wait parameters (Wait and Spies, 1964), namely the reference height and conductivity gradient that are affected the electrical conductivity in the reflection height.

D-region is controlled by ionization/recombination processes, atmospheric chemistry and dynamics. It is essentially maintained by the solar Lyman-alpha radiation (121.6 nm) during quiet conditions (Nicolet and Aikin, 1960) that ionizes the neutral atmospheric constituent nitric oxide (NO). It is strongly affected by solar flares, when the excess of soft X-ray emission produces significant enhancements of NO ionization at heights below 70 km, and of O2 and N2 molecules (Nicolet and Aikin, 1960) at higher heights. These ionization enhancements are detected as abrupt phase variations of the VLF signals, the called sudden phase anomalies (SPAs). The size of the SPAs depends on the X-ray flare fluxes (Chilton et al., 1963; Crombie, 1965; Grubor et al., 2005; Kaufmann et al., 2002; McRae and Thomson, 2004). SPA studies have shown that the D-region conductivity and reference height present different characteristics as a function of the solar activity level. The reference height of quiescent ionosphere was found to be about 1 km lower at solar maximum compared to that at solar minimum (McRae and Thomson, 2004; Raulin et al., 2006). VLF studies also had shown that the lower ionosphere is more sensitive during the periods the solar activity is at lower levels, when even weaker solar X-ray events produce significant phase advances (McRae and Thomson, 2000; Pacini and Raulin, 2006; Raulin et al., 2010).

Thomson and Clilverd (2000) showed that the mid-day VLF amplitude decreases during the declining of the solar activity due the reduction of the solar Lyman-alpha ionizing radiation. On the other hand, the lower ionosphere studies have shown it is not only controlled by solar phenomena, but it is also affected by meteorological processes occurring in the neutral atmosphere (e.g., Lastovicka 2006, 2009).

The atmospheric control in the D-region occurs predominantly during wintertime, the so called 'winter anomaly' (e.g., Offermann, 1978). The 'winter anomaly' has been observed as excessive enhancements of both the average level and especially day-to-day variability of radio-wave absorption (Taubenheim, 1983). These absorptions have been attributed to electron density increases in the lower ionosphere, and are attributed to the influence of planetary waves (PW) that propagate upwards (e.g. Lastovicka et al., 1994; Pancheva et al., 1989). Kawahira (1985) found that the lower ionosphere absorptions observed during the 'winter anomaly' are produced by density increases due the income NO-rich air from high latitudes under the influence of large-amplitude planetary wave winds that change the horizontal distribution of NO at middle latitudes.

The effects of meteorological processes have been also observed in C-region as evident disturbances observed at sunrise times during ~90 min (Chilton et al., 1964; Mechtly and Smith, 1968; Mechtly et al., 1967; Rasmussen et al., 1980). Strong VLF phase fluctuations of the C-region were observed in close association with stratosphere temperature variations measured during wintertime as reported by Gavilán (2009), reinforcing the idea of the influence of meteorological processes in the lower ionosphere.

In this paper we present the lower ionosphere behavior obtained from VLF observations done from 2004 to 2008 at Comandante Ferraz Brazilian Antarctic Station (EACF). The analysis is based on measurements of mid-day amplitude of VLF signals at 21.4 kHz from the US Navy transmitter in

Lualualei/Hawaii (NPM). We present and discuss the daytime lower ionosphere behavior considering the effects of solar forcing from above and the meteorological effects (atmospheric waves) from below.

2. Instrumentation and data analysis

The VLF measurements were done with a narrowband tunable receiver (Johnson et al., 1999) operating at EACF (62.1ºS, 58.4ºW, L=2.24). This receiver was configured to demodulate only the amplitude of the VLF signals with 20 ms time resolution. The data analysis considered the VLF signals detected at 21.4 kHz from NPM transmitter (20.4°N, 158.2°W, Lualualei in Hawai), propagating in the great circle path (GCP) NPM-EACF. This GCP has about 12 Mm of extension, it is totally over the ocean surface and mostly in the southern hemisphere (Fig. 1(a)). A typical 1-day observation of NPM signal detected at EACF is showed in Fig. 1(b), where the night- and day-time hours in this path are identified.

To evaluate the lower ionosphere behavior we used the mid-day VLF amplitude measured in the GCP NPM-EACF that is the 1-hour averaged amplitude obtained between 19:00 and 20:00 UT (small box over the amplitude curve in Fig. 1(b)). The analysis covers the period from 2004 to 2008, and the days with solar flares occurring in the mid-day time window were discarded. During all the period of analysis the amplitude calibration remained reasonably stable.

The mid-day VLF amplitude data was compared with the solar Lyman-alpha radiation (121.6 nm) to evaluate the influence of the solar forcing in the lower ionosphere. The solar Lyman-alpha data used here was obtained from EUV Grating Spectrograph (EGS) in the Solar EUV Experiment (SEE) instrument (Woods et al., 1994) on board of the Thermosphere Ionosphere Mesosphere Energetic and Dynamics (TIMED) satellite. We used the TIMED SEE Level 3 data files that give the daily averaged solar Lyman-alpha radiation correct for atmospheric absorption, degradation, flare removal, and reduced to 1AU (http://lasp.colorado.edu/see/l3_data_page.html).

The atmosphere conditions were evaluated using middle latitude averaged stratosphere parameters measured at 10 hPa (40 km), obtained from U. S. National Centers for Environment Prediction (the NCEP data link can be obtained in the site http://acdb-ext.gsfc.nasa.gov/Data_services/met/ann_data.html#ncep_clim_stats_sh and http://acdb-ext.gsfc.nasa.gov/Data_services/met/ann_data_help.html). The stratosphere parameters we used here are: (a) temperature (Tmid) averaged between 55^o and 75^o, (b) momentum flux averaged between 45^o and 75^o, and (c) zonal wind (ZW) at 60^0 S. The momentum flux is an indicator of the disturbance level of the stratosphere because it is calculated by correlating the meridional wind and the longitudinal asymmetries of the ZW. The ZW parameter at 60^{o}S is an indicator of the strength of the polar vortex, because its edge is located around this latitude (Waugh and Randel, 1999). We also considered the stratosphere temperature measured over EACF by SABER experiment onboard TIMED satellite (http://saber.gats-inc.com), when it was crossing a region of about 10^o x 10^o at 60-70 km of height over the EACF.

3. Observational results

The mid-day VLF amplitude behavior observed from 2004 to 2008 (Fig. (2b)) shows an annual well defined behavior. It was relatively stable from December to March (local summer season) in all years, when the amplitude variations were ≤ 1 dB. On the other hand, it presented amplitude variations of about 5 dB from April through October (called here the wintertime, and identified by the vertical boxes in Fig. 2). The error in the determination of the VLF amplitude was estimated from the rms of the measurements, which gives a σA ~ 0.1 dB.

To evaluate the solar forcing of the lower ionosphere, the VLF amplitude was compared with the 27-day smoothed solar Lyman-alpha flux (Fig. (2a)). The forcing from below was evaluated comparing the VLF amplitude with the daily averaged stratosphere parameters: temperature (Tmid) (Fig. (2c)), zonal wind (Fig. (2d)) and momentum flux (Fig. (2e)) measured at southern midlatitudes. The results are discussed in the 3.1 and 3.2 Sections, respectively.

3.1. Solar forcing of the lower ionosphere

The influence of the solar radiation in the lower ionosphere is evaluated considering the level of the mid-day VLF amplitude on January/December months (summertime), when it is more stable (Fig. 2). The VLF amplitude during summertime shows a slow decrease each year, being ~26 dB on January 2004 and ~23 dB on December 2008 that gives a decrease rate ~0.6 dB/year. The decrease of the VLF amplitude means that the electron density in the lower ionosphere decreased each year, as expected, because the period of analysis covered the declining phase of the 23rd solar cycle, when the solar Lyman-alpha ionizing radiation was decreasing.

The decrease rate of the VLF amplitude obtained here, during the decay of 23rd solar cycle, is comparable with the rate of ~0.7dB/year obtained by Thomson and Clilverd (2000) during the beginning of the declining phase of the 22nd solar cycle in a similar propagation path. The decrease of VLF amplitude signals is produced by the variation of the D-region conductivity, which is controlled by the solar ionizing radiation.

To study the solar forcing in the D-region along the year, especially from April to October (wintertime), we compared the 7-day smoothed mid-day VLF amplitude (Fig. 3(a)) with the 27-day smoothed Lyman-alpha radiation flux (Fig. 3(b)) each year. During the wintertime, the VLF amplitude shows a complex behavior not explained by the variation of the solar radiation (Fig. (3b)). It shows an overall decrease produced by the reduction of the solar illumination, as expected, but also suggests an interannual variation. The interannual variation is characterized by VLF amplitudes higher in odd years (2005 and 2007), and lower amplitudes in even years (2004 and 2006). This behavior suggests a close association with the biennial variation of the stratosphere temperature; because the higher VLF amplitudes occurred in the years the stratosphere was warmer. The biennial atmosphere variations is attributed to the interaction between atmospheric waves propagating upwards and the averaged zonal wind (Labitzke, 1980; Shepherd, 2000).

3.2. Forcing of the lower ionosphere from below

The interannual variation of the mid-day VLF amplitude observed from April to October (wintertime) is very suggestive of the lower ionosphere response to 'meteorological processes' originated in the lower-lying atmospheric layers. This suggestion is reinforced by the presence of strong fluctuations of the VLF amplitude during wintertime that appeared when the stratosphere becomes disturbed, as indicated by the momentum flux parameter (Fig. (4)), evidencing the meteorological processes affecting the lower ionosphere.

During wintertime the VLF amplitude shows evident fluctuations with time scale of few days (Fig. 4). The fluctuations present higher amplitudes (~5 dB) from April to August (autumn to mid-winter), appearing when the stratosphere is cooling (Fig. (2c)) and the zonal wind is accelerating in the eastward (westerly) direction. From September to October (mid-winter to winter/spring transition) the amplitude of the fluctuations decreases (~2 dB) when the stratosphere is warming and becomes turbulent, and eastward zonal wind is decelerating. However, during summertime, the fluctuations are no more evident and now the stratosphere returned to its quiet state and the zonal wind is westward (easterly).

To characterize the fluctuations observed in the VLF amplitude, the data time series for each year was analyzed using a wavelet transform. We used a Morlet mother wavelet with frequency parameter equal 6, significance level of 95% and time lag of 0.72 (for details e.g. Torrence and Compo 1998). The analysis shows the fluctuations present a tendency to have periods in the range of 12-20 days, 8-10 days and ~5 days (Fig. 5). The wavelet amplitude spectra shows the most significant fluctuations are in the period range of 12-20-days. This component shows a well-defined seasonal behavior, being stronger during wintertime (amplitude ~ 2-5 dB), but it is also weakly present from November to March (summertime) (VLF amplitude ≤ 1 dB) (Fig. 5).

The longer-period fluctuations we detected here can be associated with the 16-day planetary wave, also observed in the mesosphere and lower thermosphere (MLT), during the same years, by Day and Mitchell (2010) from meteor radar measurements done at Rothera (68^oS, 68^o W). The 16-day wave has been detected in the MLT region from observations of wind, temperature and geopotential height (e.g., Espy and Witt, 1996; Espy et al., 1997; Forbes et al., 1995; Jiang et al., 2005; Luo et al., 2000, 2002a,b; Manson et al., 2003; Mitchell et al., 1999). It has been interpreted as a manifestation of the large amplitude Rossby waves that theoretically occur with periods between 11-20 days (Salby, 1984). The studies of the 16-day wave activity have shown a clear seasonal behavior with the maximum in winter (Mitchell et al., 1999; Luo et al., 2000, 2002a), when the zonal wind is eastward (westerly). This behavior can be explained considering that the PW propagation from the lower atmosphere to the MLT is controlled by winds and that eastward stratospheric zonal wind observed during wintertime (Fig. 4) favors the vertical propagation of large-scale PWs (Charney and Drazin, 1961).

The wavelet analysis also suggests an interannual variation of the properties of the 16-day wave in the lower ionosphere. In odd years (2005 and 2007) the analysis show a strong component with 16 days period, but in even years the period of this component is lower (12 days on 2004) or it is weakly present (2006). This behavior was also detected in the zonal wind data measured over Rothera, which showed the amplitude of the 16-day wave was lower in 2006 compared with to 2007 (Day and Mitchell, 2010). The suggestive interannual variation of the VLF amplitude in close association with the stratosphere temperature during wintertime could be explained by the influence of the stratosphere conditions that are controlled by the variability and vertical structure of the planetary wave activity (Labitzke, 1980).

To evaluate the connection between the lower ionosphere behavior and the stratosphere dynamics, we applied the wavelet analysis to the stratosphere temperature measured over EACF by the SABER experiment. The analysis was performed for 2007 because the VLF time series has less data gaps than other years. The stratosphere temperature wavelet analysis shows the 16-day wave, as well another component with period in the range of 5-10 days, both components presenting stronger activity during the wintertime. These results show the periodic components detected in the stratosphere temperature present the same behavior observed in the lower ionosphere, which reinforces the evidence for the coupling between the lower ionosphere and the stratosphere. The results found here are in agreement with long-term studies of the variability of long-period planetary waves in the stratosphere (e.g. Fedulina et al., 2004) that have shown that these waves increase in amplitude during local wintertime and that in the southern hemisphere the eastward-propagating waves prevail.

The large fluctuations of the VLF amplitude are explained by electron density enhancements in the D-region that can be attributed to an excess of NO transported from higher to middle latitudes under the influence of large-amplitude planetary wave winds (Cravens and Stewart, 1978; Iwagami and Ogawa, 1980; Kawahira, 1985). This is the same used to explain the radio wave absorptions observed during the ‘winter anomaly’. During wintertime, the NO at polar region is abundant due the descent NOx from the thermosphere into the stratosphere under the action of the polar vortex (Clilverd et al., 2007; Randall et al., 2009; Seppala et al., 2007).

In summary, we showed that during wintertime the lower ionosphere at middle southern latitudes is strongly affected by ‘meteorological processes’, particularly during low solar activity. D-region behavior shows clearly the influence of 16-day PW, which presented well-defined seasonal cycle showing larger amplitude predominantly during wintertime, when the zonal wind was westerly. This behavior is in agreement with the Charney and Drazin´s theorem (1961) that states that the westerly stratospheric winds favor the vertical propagation of the PWs. The analysis also suggested an interannual variation in the 16-day wave component, which was also observed in Antarctic MLT wind and temperature data as reported by Day and Mitchell (2010). These correlations provide further evidence of the coupling between the lower ionosphere and the stratosphere.

4. Concluding remarks

The 5-years study of the ionosphere using VLF measurements is presented in this work. The external forcing of the lower ionosphere was investigated from mid-day VLF amplitude measurements done at Comandante Ferraz Brazilian Antarctic Station from 2004 to 2008. The main conclusions are:

The mid-day VLF amplitude data showed clearly the effect of the solar forcing, as expected. The VLF amplitude decreased each year (~0.6 dB/year) in close association with the reduction of the solar Lyman-alpha ionizing radiation during the declining of the 23rd solar cycle.

The VLF amplitude also showed an interannual and seasonal variability, evidencing the 'meteorological processes' affecting the lower ionosphere. The strong fluctuations observed in the VLF amplitude, especially during wintertime, are the effects of PWs originated in the neutral atmosphere that propagated freely upwards favored by the westerly winds. The wavelet spectral analysis showed the 16-day PW was the most important component affecting the lower ionosphere and it was also reported in observations of wind and temperature done in the MLT region.

This study showed that the lower ionosphere behavior has a close association with the dynamics of the lower-lying layers of the atmosphere, especially during the local wintertime, when the vertical propagation of the PWs is favored by the westerly winds.

Long term studies of the effects of waves coming from below into the ionosphere are desirable for understanding the vertical couplings between the different layers of the atmosphere, and how the energy exchange between them is. It is necessary to consider the interactions between the different upward propagating waves in the neutral atmosphere. 16-day PW modulation of the amplitude of the

12 h tide in the MLT region was already reported that was attributed to a non-linear interaction of the tide wave with the PWs (Pancheva et al., 2002).

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Fig. Captions

Fig. 1. (a) VLF propagation path from the NPM transmitter to the receiver station at Comandante Ferraz Antarctic Station (EACF). (b) Typical NPM daily amplitude variation observed at EACF. The small box over the amplitude curve shows the time window where the mid-day VLF amplitude was obtained.

Fig. 2. Comparison of the mid-day VLF amplitude of NPM signal detected at EACF (b) with: the 27-day smoothed solar Lyman-alpha irradiance (a), and the stratosphere temperature (c), zonal wind (d) and momentum flux (e) measured at southern midlatitudes (NCEP).

Fig. 3. Year-to-year variation of the 7-day smoothed mid-day VLF amplitude (a) compared with the 27-day smoothed solar Lyman-alpha flux (b) and the averaged stratosphere temperature (NCEP) measured at middle latitudes (c) from 2004 to 2008.

Fig. 4. Annual variation of the mid-day VLF amplitude (thick lines) compared with respective momentum flux parameter of the stratosphere (thin lines) from 2004 to 2008 (curves in the top of figure). The zonal wind at each year showed in the bottom curves.

Fig. 5. Wavelet analysis of the mid-day VLF amplitude from 2004 to 2007 (a to d).

Fig. 6. Wavelet analysis of the mid-day VLF amplitude (a) and of the stratosphere temperature (b) for 2007. The stratosphere temperature used here was measured with SABER experiment over the EACF at ~70 km of height during daytime.

Highlights

- Daytime VLF amplitude measurements characterizing the forcing in the ionosphere
- Influence of ‘meteorological processes’ in the ionosphere during the wintertime
- Detection of the 16-day planetary wave in the lower ionosphere

Figure1

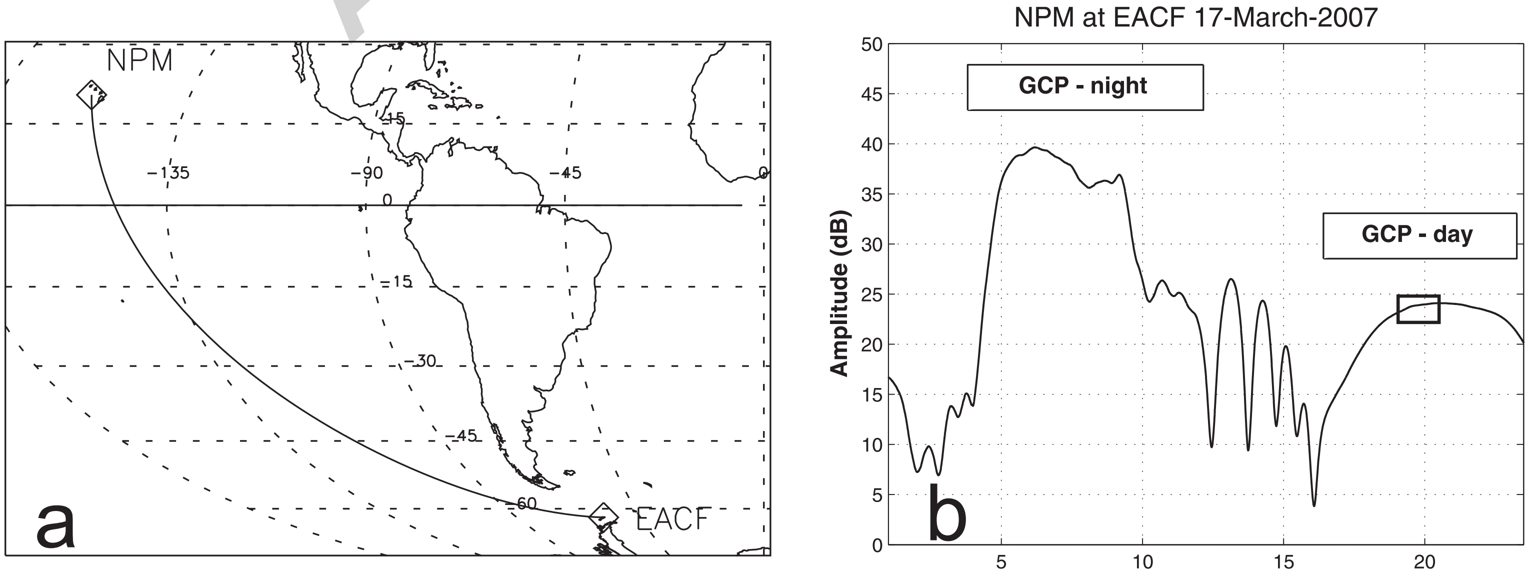

NPM
EACF
−135
−90
−45
0
15
0
−15
−30
−45
−60
a
NPM at EACF 17-March-2007
GCP - night
GCP - day
Amplitude (dB)
Hour (UT)
0
5
10
15
20
25
30
35
40
45
50
5
10
15
20
b

Figure2

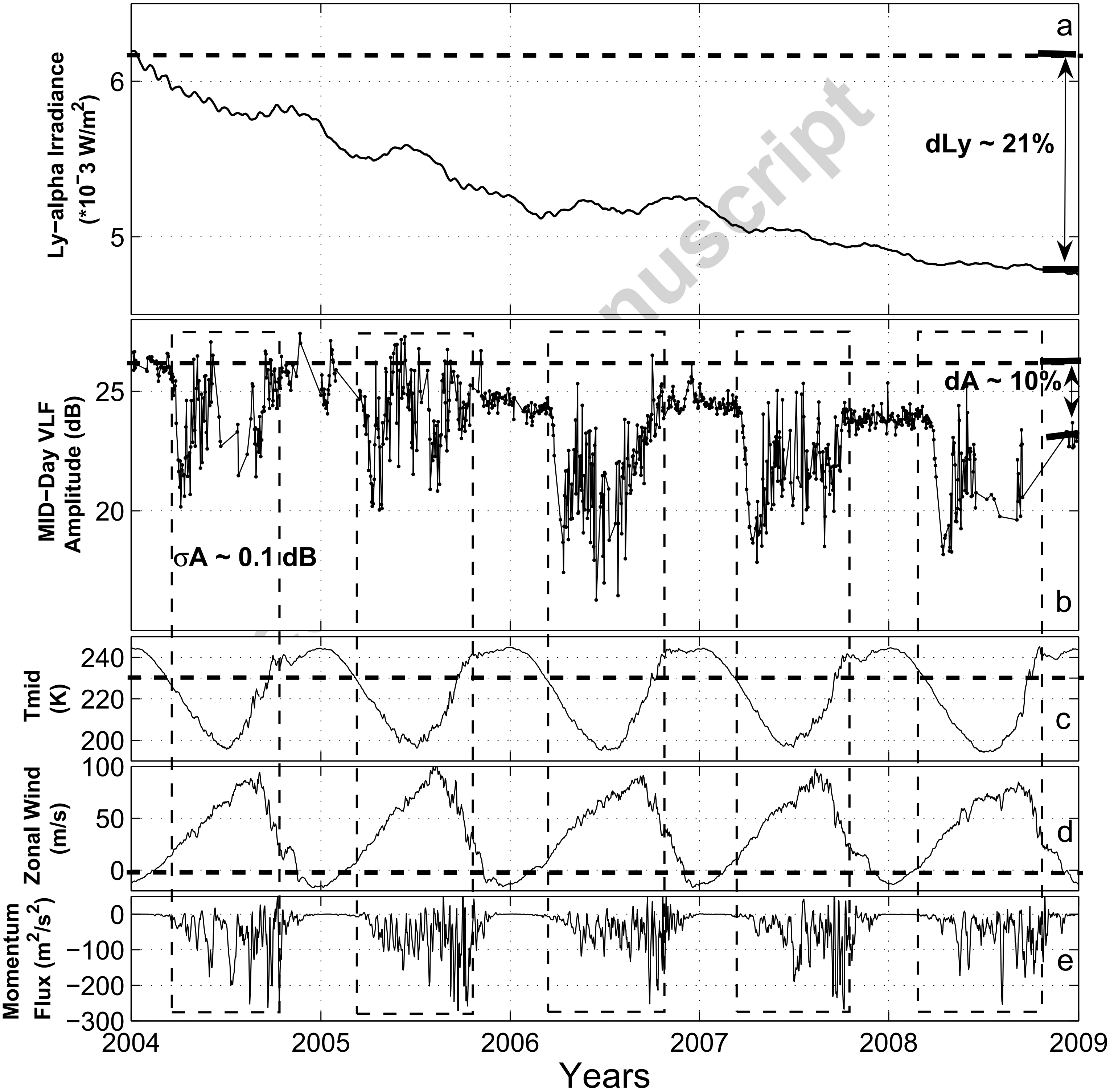

Ly−alpha Irradiance (*10⁻3 W/m²)
6
5
dLy ~ 21%
a
MID−Day VLF Amplitude (dB)
25
20
dA ~ 10%
σA ~ 0.1 dB
b
Tmid (K)
240
220
200
c
Zonal Wind (m/s)
100
50
0
d
Momentum Flux (m²/s²)
0
−100
−200
−300
e
2004
2005
2006
2007
2008
2009
Years

Figure3

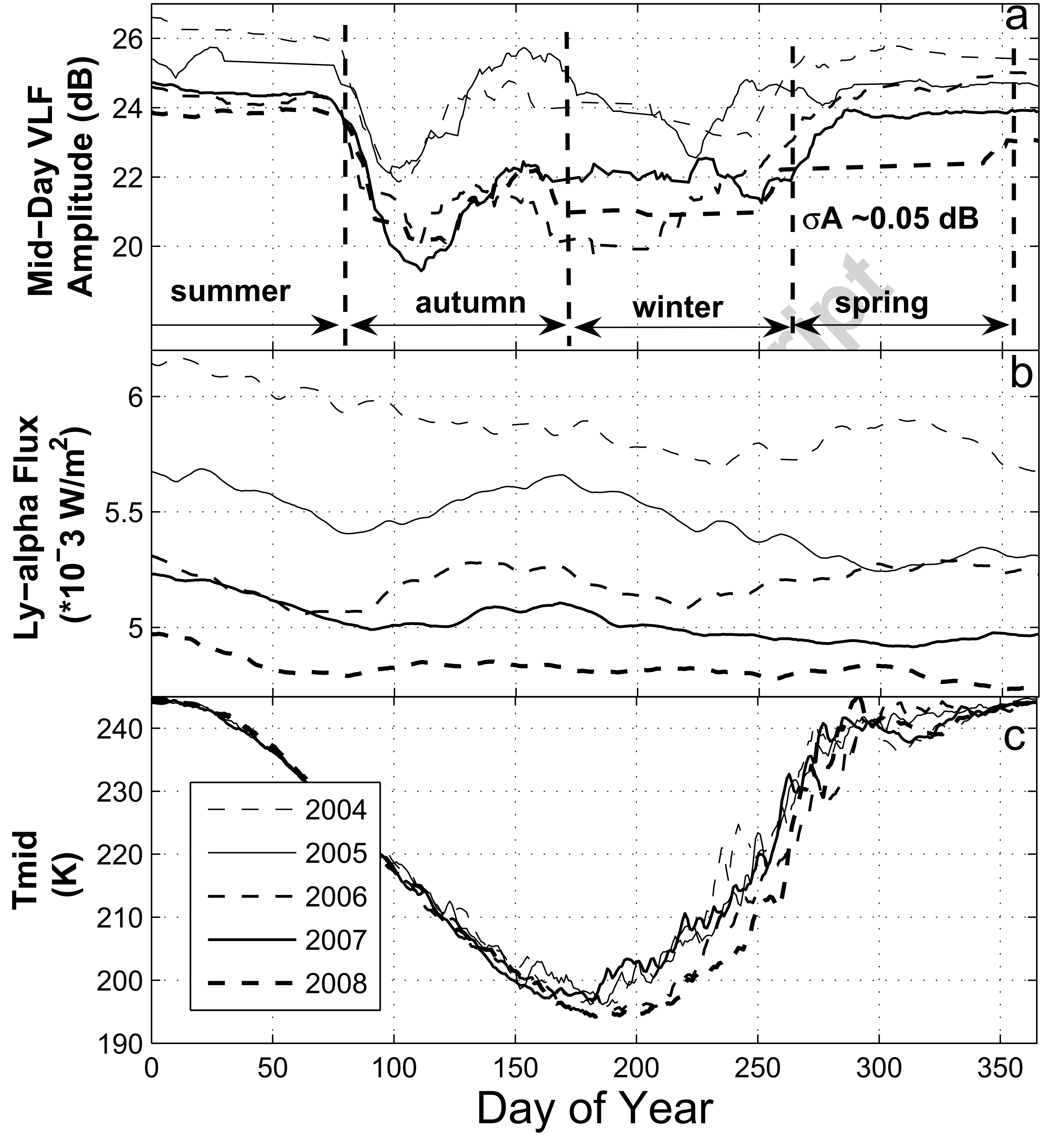

a
b
c
Mid−Day VLF Amplitude (dB)
26
24
22
20
summer
autumn
winter
spring
σA ~0.05 dB
Ly−alpha Flux (*10^−3 W/m^2)
6
5.5
5
Tmid (K)
240
230
220
210
200
190
2004
2005
2006
2007
2008
0
50
100
150
200
250
300
350
Day of Year

Figure4

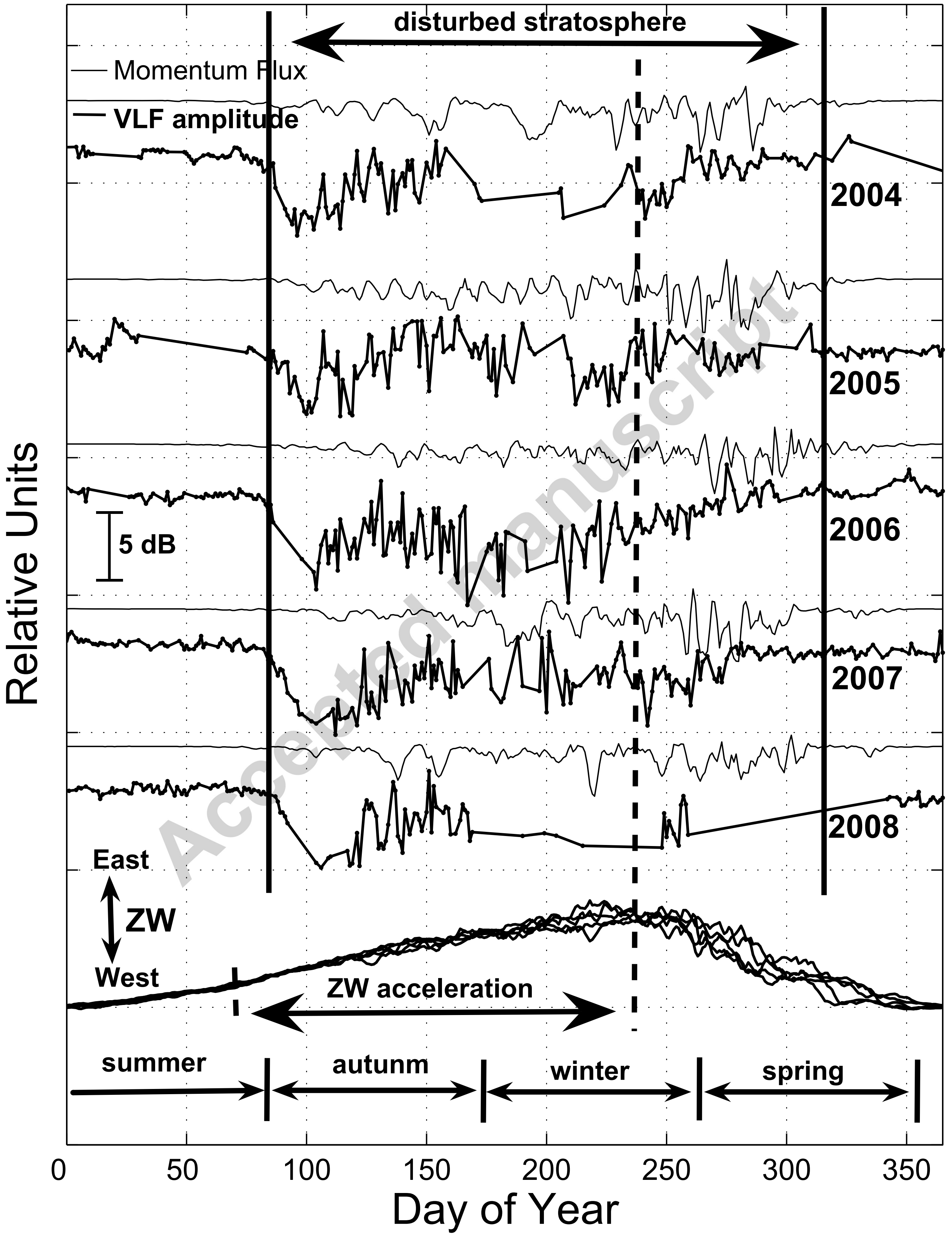
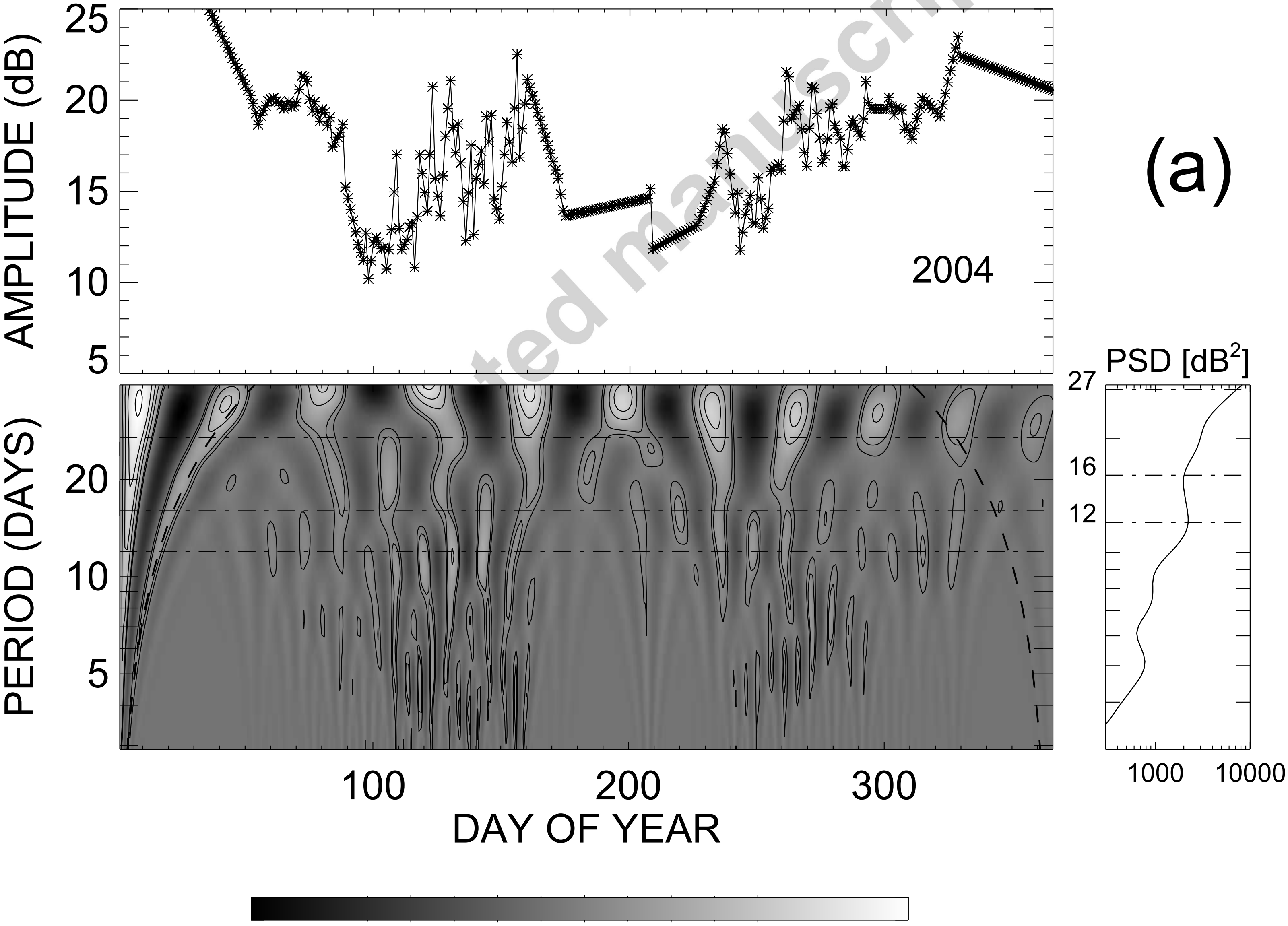
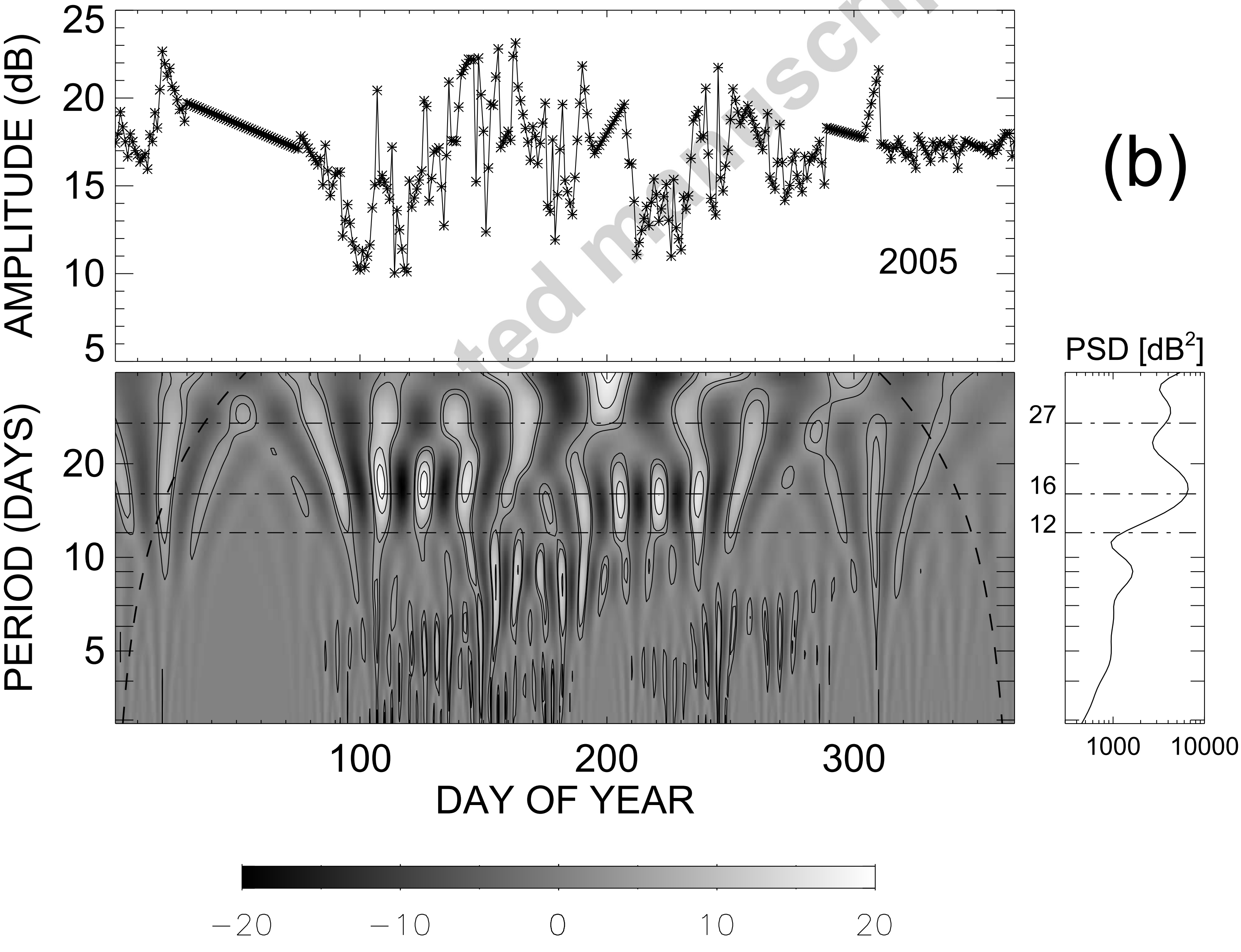

disturbed stratosphere
Momentum Flux
VLF amplitude
2004
2005
2006
2007
2008
5 dB
Relative Units
East
ZW
West
ZW acceleration
summer
autunm
winter
spring
0
50
100
150
200
250
300
350
Day of Year

Figure5a



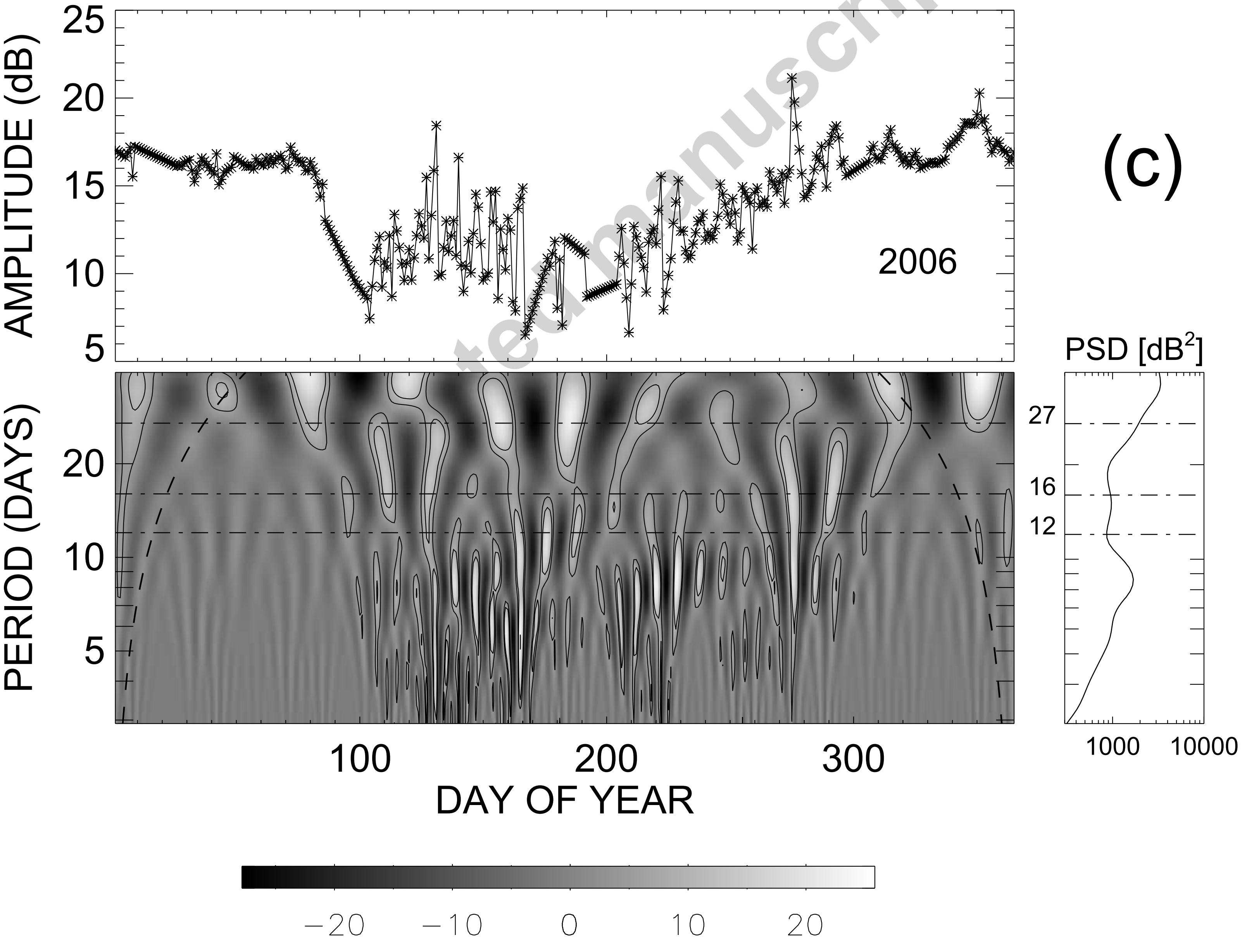
AMPLITUDE (dB)
25
20
15
10
5
2004
(a)
PERIOD (DAYS)
20
10
5
100
200
300
DAY OF YEAR
PSD [dB^2]
27
16
12
1000
10000
−20
−10
0
10
20

Figure5b



AMPLITUDE (dB)
25
20
15
10
5
2005
(b)
PERIOD (DAYS)
20
10
5
PSD [dB^2]
27
16
12
1000
10000
100
200
300
DAY OF YEAR
−20
−10
0
10
20

Figure5c


AMPLITUDE (dB)
25
20
15
10
5
2006
(c)
PERIOD (DAYS)
20
10
5
PSD [dB^2]
27
16
12
1000
10000
100
200
300
DAY OF YEAR
−20
−10
0
10
20

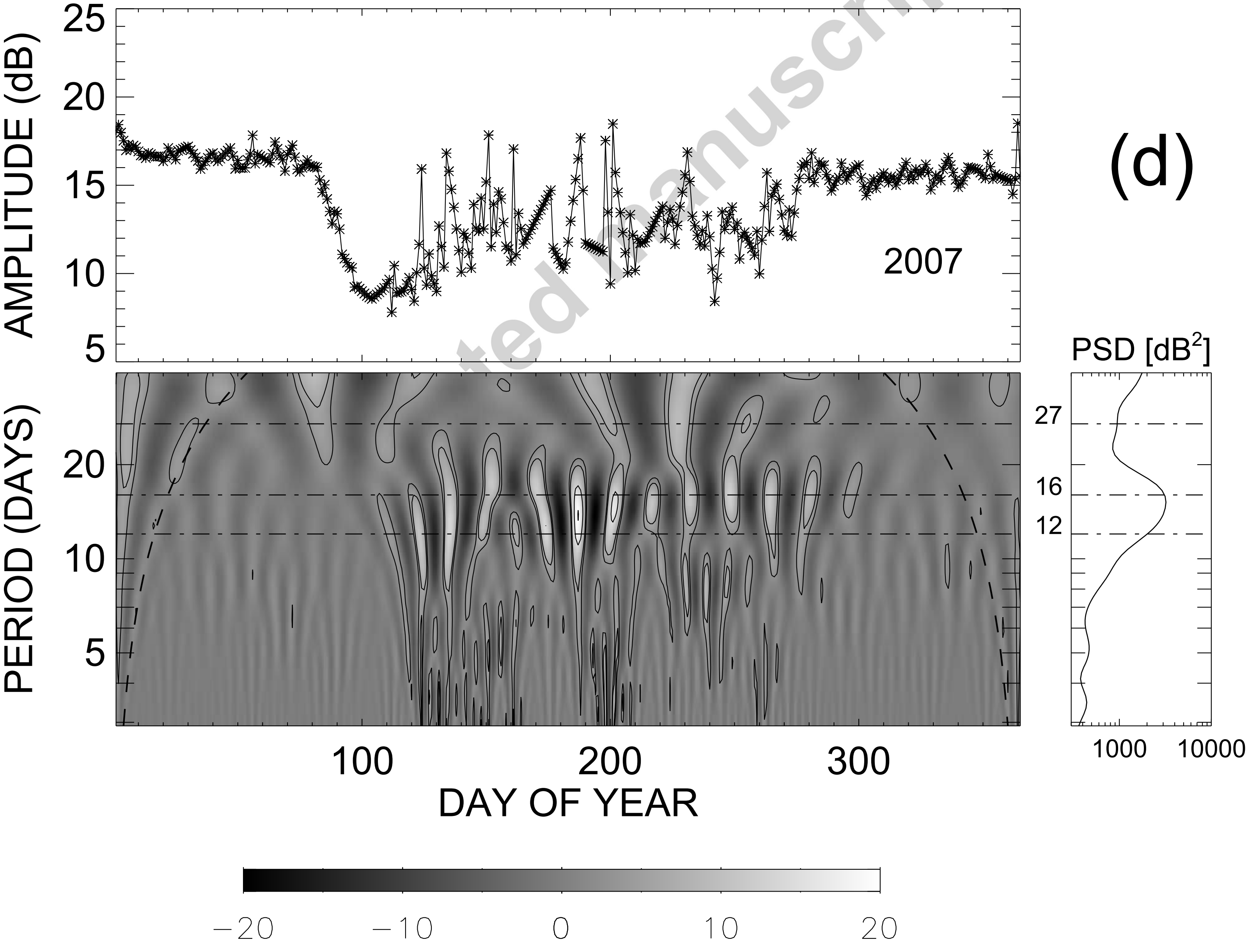
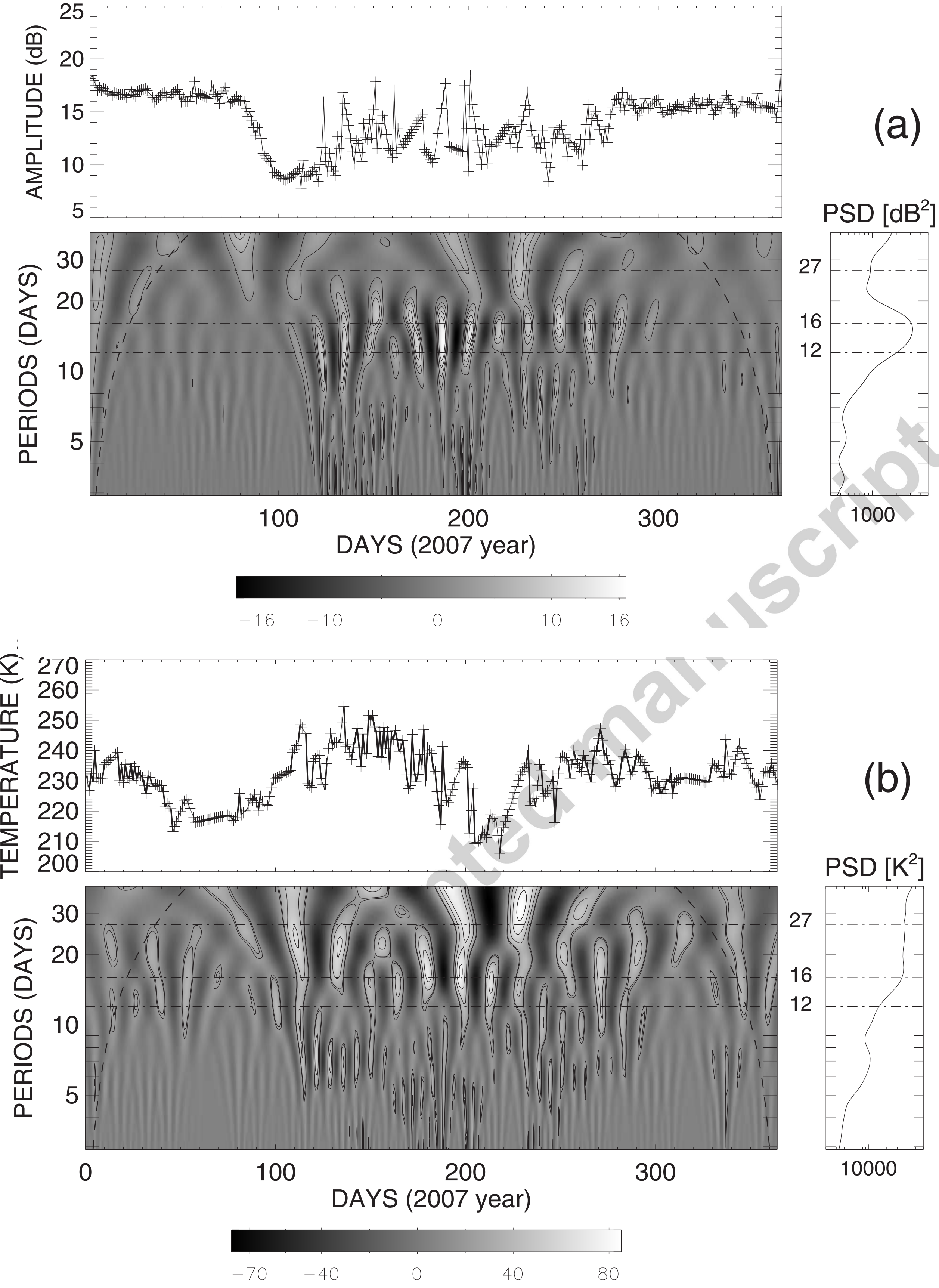

25
20
15
10
5
AMPLITUDE (dB)
2007
(d)
PSD [dB^2]
27
16
12
20
10
5
PERIOD (DAYS)
100
200
300
DAY OF YEAR
1000
10000
−20
−10
0
10
20

Figure6



AMPLITUDE (dB)
25
20
15
10
5
(a)
PERIODS (DAYS)
30
20
10
5
PSD [dB^2]
27
16
12
1000
100
200
300
DAYS (2007 year)
−16
−10
0
10
16
TEMPERATURE (K)
270
260
250
240
230
220
210
200
(b)
PERIODS (DAYS)
30
20
10
5
PSD [K^2]
27
16
12
10000
0
100
200
300
DAYS (2007 year)
−70
−40
0
40
80