Journal of Atmospheric and Solar-Terrestrial Physics 168 (2018) 1–7

Contents lists available at ScienceDirect

Journal of Atmospheric and Solar-Terrestrial Physics

journal homepage: www.elsevier.com/locate/jastp

The observational and empirical thermospheric CO_2 and NO power do not exhibit power-law behavior; an indication of their reliability

C.A. Varotsos *, M.N. Efstathiou

Department of Environmental Physics and Meteorology, National and Kapodistrian University of Athens, Athens, Greece University Campus Bldg. Phys. V, Athens 15784, Greece

ARTICLE INFO

Keywords:
Thermosphere
Power-law
Satellite observations
Climate components

ABSTRACT

In this paper we investigate the evolution of the energy emitted by CO_2 and NO from the Earth's thermosphere on a global scale using both observational and empirically derived data. In the beginning, we analyze the daily power observations of CO_2 and NO received from the Sounding of the Atmosphere using Broadband Emission Radiometry (SABER) equipment on the NASA Thermosphere-Ionosphere-Mesosphere Energetics and Dynamics (TIMED) satellite for the entire period 2002–2016. We then perform the same analysis on the empirical daily power emitted by CO_2 and NO that were derived recently from the infrared energy budget of the thermosphere during 1947–2016. The tool used for the analysis of the observational and empirical datasets is the detrended fluctuation analysis, in order to investigate whether the power emitted by CO_2 and by NO from the thermosphere exhibits power-law behavior. The results obtained from both observational and empirical data do not support the establishment of the power-law behavior. This conclusion reveals that the empirically derived data are characterized by the same intrinsic properties as those of the observational ones, thus enhancing the validity of their reliability.

1. Introduction

Recent analyses of the observations conducted by the Sounding of the Atmosphere using Broadband Emission Radiometry (SABER) instrument on the TIMED satellite provided the rates of infrared radiative cooling in terms of global radiated power (Watts) by CO_2 and NO in the Earth's thermosphere during 2002–2009 (Mlynczak et al., 2010). In particular, the results obtained showed a large decrease in the cooling rates, fluxes, and power consistent with the declining phase of solar cycle. In addition, a substantial short-term variability in the infrared emissions throughout the entire mission duration has been observed.

Earlier, Mlynczak et al. (2008) indicated a statistically significant 9-day periodicity in the time series of daily A_p and K_p geomagnetic indexes, revealing a link between Sun and infrared energy budget of the thermosphere. This strong 9-day periodicity was also derived from the spectral analysis of the thermospheric CO_2 and NO daily global power observed during 2002–2006. .

The $F_{10.7}$, *Ap*, and *Dst* indices were recently employed (Mlynczak et al., 2016) in the linear regression fitted to the time series of the thermospheric CO_2 and NO daily global power during 2002–2016, in order to develop the radiative cooling time series from 1947 to 2016. As it was derived, the total infrared energy radiated by the thermosphere, integrated over a solar cycle, seemed to be almost constant over the studied period, a fact that may assess the terrestrial context of the long-term record of solar-related indices.

The motivation of the present paper is to examine the consistency between the observed time series of infrared power made over 15 years by the SABER instrument on the NASA TIMED satellite and the extension of this time series back to 1947 using solar and geomagnetic indices. For this purpose we focus on the detection of long memory behavior in the daily CO_2 and NO global power radiated from the Earth's thermosphere during 1947–2016, using the above mentioned time series (Mlynczak et al., 2016). In more detail, we examine the non-linear properties of the above-said time-series, i.e. whether the fluctuations of each of these parameters at different times are positively correlated, thus exhibiting persistent long-range correlations. For example, we discuss whether there is a tendency for an increase in CO_2 or NO global power to be followed by another increase at a different time, in a power-law fashion. This is done by applying the modern technique of detrended fluctuation analysis (DFA) to the data used. It should be stressed that periodicities and corresponding harmonics affect the non-linear properties of the time series and thus must be filtered before considering the non-linear

* Corresponding author.
E-mail address: covar@phys.uoa.gr (C.A. Varotsos).

https://doi.org/10.1016/j.jastp.2018.01.006
Received 24 October 2017; Received in revised form 28 December 2017; Accepted 3 January 2018
Available online 8 January 2018
1364-6826/

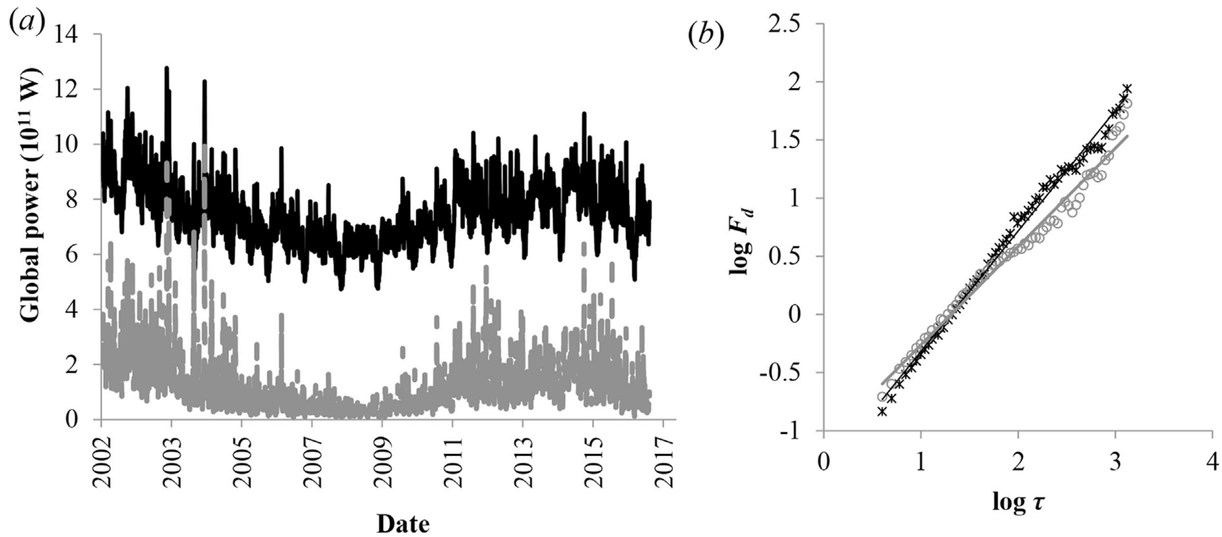

Fig. 1. (a) Temporal march of the CO_2 (black line) and NO (grey line) daily power, during the period 2002–2016. (b) The corresponding root-mean-square fluctuation functions $F_d(\tau)$ of the DFA versus time scale τ (in days), in the log-log plot and the corresponding best fit equations (CO_2: $y = 1.04x$ - 1.35 with $R^2 = 0.99$, NO: $y = 0.84x$ - 1.11 with $R^2 = 0.98$).

properties. This means that the investigation of the non-linear properties must be performed by analysing the residual time-series (filtering out the trend and harmonics). The feature of the long memory effect was earlier revealed in processes that are closely related to the total ozone content observations (Varotsos and Cracknell, 1993, 1994; Cracknell and Varotsos, 1994, 1995, 2007; Kondratyev et al., 1994; Varotsos et al., 1994, 2000, 2009a,b; Varotsos and Cartalis, 1991; Gernandt et al., 1995; Varotsos and Tzanis, 2012; Varotsos, 2002, 2005; Efstathiou et al., 2003), the air temperature (Efstathiou et al., 2011; Varotsos et al., 2009a,b), the solar ultraviolet radiation (Varotsos and Cracknell, 2004; Feretis et al., 2002; Varotsos et al., 1995; Efstathiou et al., 1998) having strong impacts to the dynamics of the climate system (Varotsos et al., 2016; Kondratyev and Varotsos, 1995; Cracknell and Varotsos, 2011; Krapivin et al., 2015; Krapivin and Varotsos, 2008, 2016; Tzanis et al., 2008, 2009, 2011; Tidblad et al., 2012).

2. Data and analysis

For the purposes of this study, we are exploring the temporal course of the daily global power (W) radiated by carbon dioxide (CO_2 at 15 μm) and by nitric oxide (NO at 5.3 μm). The NO power is obtained from an integration of the cooling rate from 100 to 250 km, while the CO_2 power derives from 100 to 139 km. CO_2 and NO daily power measurements (kindly provided by M. Mlynczak) cover 15 years from 2002 through 2016 and have been taken by the Sounding of the Atmosphere using Broadband Emission Radiometry (SABER) instrument on the NASA Thermosphere-Ionosphere-Mesosphere Energetics and Dynamics (TIMED) satellite.

We also use two more extended time series of thermospheric CO_2 and NO daily global power that cover the period from 1947 through 2016, developed recently Mlynczak et al. (2016). Specifically, for the development of this time series the following were used: the $F_{10.7}$, *Ap*, and *Dst* indices in linear regression fits to the above described data sets of CO_2 and NO power (2002–2016) to construct the infrared power emitted by NO and CO_2 back to 1947, which date is the beginning of the $F_{10.7}$ time series.

To study the scaling dynamics of all these time series, we use the DFA technique. The necessity to employ DFA modern method stems from the fact that most of the atmospheric quantities obey non-linear laws, which usually generate non-stationarities (i.e. processes whose statistical properties such as mean, variance, co-variance alter over time).

Examples of non-stationarities are trends, cycles, random walks or combination of the three (Pancheva, 2000; Pancheva et al., 2009, 2017). These non-stationarities often conceal the existing correlations into the examined time series and therefore, instead of the application of the conventional Fourier spectral analysis on the atmospheric time series, DFA-technique capable to eliminate the non-stationarities in the data should be utilize (Varotsos et al., 2008; Peng et al., 1994; Weber and Talkner, 2001; Efstathiou and Varotsos, 2010). The sequential steps of DFA are described below:

1) The time-series of the studied parameter, $y(i)$, is integrated and then separated into a set of non-overlapping boxes of equal length, τ.
2) In each box a linear local trend is fitted, in order to detrend the integrated profile (by subtracting the locally fitted trend).
3) The root-mean-square fluctuations F_d (τ) of this integrated and detrended profile is calculated over all box sizes (scales). The detrended fluctuation function F is defined by (Kantelhardt et al., 2002):

$$F^2(\tau) = \frac{1}{\tau} \sum_{i=k\tau+1}^{(k+1)\tau} [y(i) - z(i)]^2, \quad k = 0, 1, 2, \cdots, \left(\frac{N}{\tau} - 1\right) \tag{1}$$

where $z(i)$ is a linear least-square fit to the τ data contained in a box and N is the total number of data.

4) When the signals involve scaling, a power-law behavior for the root-mean-square fluctuation function F_d (τ) is observed:

$$F_d(\tau) \sim \tau^a \tag{2}$$

where α is the scaling exponent which represents the long-range power-law correlation (Ausloos and Ivanova, 2001).

A scaling exponent different from 0.5 ($a \neq 0.5$), in a certain range of τ values, could indicate long-range correlations in that interval, while the exponent $a = 0.5$ suggests the classical random walk (white noise). When a is between zero and 0.5, then power-law anticorrelations appear to be present (antipersistence), while exponent $a = 1$ denotes the so-called $1/f$ noise. The $1/f$ noise, with f being frequency, refers to the unique spectrum shape of signals that represents the same degree of variability for a whole spectrum range with very long lag-correlations. A scaling exponent between 0.5 and 1 could exhibit persistent power-law correlations and this persistent behavior gets even stronger when the a-exponent is between 1 and 1.5 (Weber and Talkner, 2001).