Consistency between observational and empirical data of the thermospheric CO$_2$ and NO power

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Abstract. We explore the temporal evolution of the energy radiated by CO$_2$ and NO from the Earth's thermosphere on a global scale. This investigation is based on both observational and empirically derived data. Firstly, we analyze the daily power observations of CO$_2$ and NO obtained by the Sounding of the Atmosphere using Broadband Emission Radiometry (SABER) instrument on the NASA Thermosphere-Ionosphere-Mesosphere Energetics and Dynamics (TIMED) satellite throughout the period 2002 - 2016. Secondly, we perform the same analysis to 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 employed for the analysis of the observational and the empirical datasets is the detrended fluctuation analysis, in order to investigate whether the power emitted by CO$_2$ and by NO in the thermosphere exhibits power-law behaviour. The results obtained from both the observational and empirical data do not support the establishment of the power-law behaviour. This result indicates that the empirically derived data exhibit the same intrinsic properties with the observational ones, thus enhancing their reliability.

Keywords: thermosphere; power-law; satellite observations; climate components

1. Introduction

Although many papers discuss the moderate anthropogenic temperature changes expected in the lower atmosphere, other publications predict a severe cooling (of 10±15 K) in the upper stratosphere and mesosphere, in case of CO$_2$ doubling.

Last years a few papers have presented analysis of observations of the infrared radiative cooling by CO$_2$ and NO in the Earth's thermosphere during 2002 – 2009, provided by the Sounding of the Atmosphere using Broadband Emission Radiometry (SABER) instrument on the TIMED satellite [1]. 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.
Spectral analysis on the thermospheric CO₂ and NO daily global power from 2002 through 2006 showed a statistically significant 9-day periodicity in the infrared data but not in the solar data [2]. However, a strong 9-day periodicity was also detected in the time series of daily Aₚ and Kₚ geomagnetic indexes, revealing a link between the Sun and the infrared energy budget of the thermosphere.

An empirical model has recently been presented [3], where the F₁₀.₇, Ap, and Dst indices were employed in the linear regression fitted to the time series of the thermospheric CO₂ and NO daily global power from 2002 through 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 present study aims to detect long memory behaviour in the daily CO₂ and NO global power radiated from the Earth's thermosphere during 1947-2016, by using the above mentioned time series [3]. The feature of the long memory effect was earlier revealed in processes that are closely related to the total ozone content observations [4-18], the air temperature [19-21], the solar ultraviolet radiation [22-25] having strong impacts to the dynamics of the climate system [26-31].

2. Data and analysis

We herewith examine the temporal march of the daily global power (W) radiated by carbon dioxide (CO₂ at 15 μm) and by nitric oxide (NO at 5.3 μm) from the Earth's thermosphere between 100 km and 139 km altitude. CO₂ and NO daily power measurements (kindly provided by M. Mlynczak) cover 15 years from 2002 through 2016 (see [1-4] 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 employ two more extended time series of thermospheric CO₂ and NO daily global power that cover the period from 1947 through 2016, developed recently [3]. Specifically, for the development of this this time series the following were used: the F₁₀.₇, Ap, and Dst indices in linear regression fits to the above described data sets of CO₂ and NO power (2002-2016) to construct the infrared power emitted by NO and CO₂ back to 1947, which date is the beginning of the F₁₀.₇ time series.

To study the scaling dynamics of all these time series, we use the DFA technique, which eliminates the noise of the non-stationarities that characterize the time series of CO₂ and NO daily power and permits the detection of intrinsic self-similarity [32-34]. The sequential steps of DFA are described in [34] and a detailed description is presented in [21].

The strong long-term trend and seasonality that characterize the time series of CO₂ and NO daily power are both removed (deseasonalization and detrending) by using the classical Wiener method [35] and the polynomial regression analysis, respectively.

In order to confirm the existence of long-range correlations in the time series of CO₂ and NO daily power, the autocorrelation function and the method of the local slopes of the fluctuation functions are also employed (i.e. the two criteria proposed in [36]).
3. Results and discussion

Our first step was to explore the temporal evolution of CO\(_2\) and NO daily power, for the period 2002-2016. The initial time series are shown in Figure 1(a), while the corresponding root-mean-square fluctuation functions \(F_d(\tau)\) of the DFA technique versus time scale \(\tau\) (in days), are depicted in Figure 1(b).

![Figure 1](image)

**Figure 1.** (a) Temporal march of the CO\(_2\) (black line) and NO (gray 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 \(\tau\) (in days), in log-log plot and the respective best fit equations (CO\(_2\): \(y = 1.04x - 1.35\) with \(R^2 = 0.99\), NO: \(y = 0.84x - 1.11\) with \(R^2 = 0.98\)).

The derived DFA scaling exponent for the initial time series of CO\(_2\) (NO) daily power was found \(a = 1.04 \pm 0.01\) (\(a = 0.84 \pm 0.02\)), assuming therefore long-range persistence (of 1/f – type for the case of CO\(_2\)). However, to reliably establish power-law scaling and long-range correlations for the temporal march of CO\(_2\) and NO daily power, the autocorrelation function and the local slopes \(a\) vs log\(\tau\) should be investigated in relation to the criteria proposed in [36].

Specifically, Figure 2(a and b) presents the profiles of the power spectral density for the time series of CO\(_2\) and NO daily power, showing therefore that the exponential decay could be rejected only for the case of CO\(_2\), where power-law fit seems to give a little better coefficient of determination. Regarding the second criterion of [36], we fitted a straight line to log\(F_d(\tau)\) vs. log\(\tau\) (for both CO\(_2\) and NO daily power) within a small window, shifting it successively over all calculated scales \(\tau\). However, local slope \(a\) vs. log\(\tau\) seemed to fluctuate without any interval of constancy, indicating thus that long-range correlations of power-law type could not be established either for CO\(_2\) or for NO daily power (see Figure 3(a and b)).

Our second step was to re-apply the above described analysis on the detrended and deseasonalised time series of CO\(_2\) and NO daily power, for the period 2002-2016 (see Figure 4(a and b). The derived DFA scaling exponent for the time series of CO\(_2\) (NO) daily power was found \(a = 0.78 \pm 0.01\) (\(a = 0.63 \pm 0.01\)), assuming again long-range persistence.
Figure 2. Power spectral density for the initial time series of (a) CO₂ daily power and (b) NO daily power (from 2002 to 2016), with the corresponding power-law (grey dashed line) and the exponential (grey solid line) fit (CO₂: $y = 1.54 \times 10^{-6}x^{-1.23}$ with $R^2 = 0.44$ and $y = 8.72 \times 10^{-5}e^{7.84x}$ with $R^2 = 0.39$, NO: $y = 4.6 \times 10^{-6}x^{-0.97}$ with $R^2 = 0.34$, $y = 1.26 \times 10^{-4}e^{-6.68x}$ with $R^2 = 0.35$).

Figure 3. Local slopes of the $\log F_d (\tau)$ vs. $\log \tau$ (10-base logarithms) calculated within a window of 18 points (dashed grey line), of 12 points (solid thin black line) and of 15 points (dashed black line) for the initial time series of (a) CO₂ daily power and (b) NO daily power. The error bars indicate the corresponding 1.96σ intervals of the slopes over all the considered scales.

Nevertheless, according to Figure 5(a,b) and Figure 6(a,b), the conditions of [36] seemed not to be satisfied, indicating once more that power-law scaling can not be established for the detrended and deseasonalised time series of CO₂ and NO daily power. It is worthy of note that only for the case of NO, there seems to be a constancy of the local slopes $\alpha$ vs. $\log \tau$ in a small range, which is not however enough to confirm the long-range correlations.
Figure 4. (a) Detrended and deseasonalised temporal march of the CO$_2$ (black line) and NO (gray 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 $\tau$ (in days), in log-log plot and the respective best fit equations (CO$_2$: $y = 0.78x - 1.12$ with $R^2 = 0.99$, NO: $y = 0.63x - 0.87$ with $R^2 = 0.98$).

Figure 5. Power spectral density for the detrended and deseasonalised time series of (a) CO$_2$ daily power and (b) NO daily power (from 2002 to 2016), with the corresponding power-law (grey dashed line) and the exponential (grey solid line) fit (CO$_2$: $y = 1.95 \times 10^{-5}x^{-1.06}$ with $R^2 = 0.36$ and $y = 7.31 \times 10^{-6}e^{-7.31x}$ with $R^2 = 0.37$, NO: $y = 5.5 \times 10^{-6}x^{-0.85}$ with $R^2 = 0.28$, $y = 1.1 \times 10^{-4}e^{-6.31x}$ with $R^2 = 0.33$).

In the following, we studied the two other time series mentioned in the section 2, i.e. the radiated CO$_2$ and NO daily power, empirically derived from the infrared energy budget of the thermosphere from 1947 to 2016. The initial time series are shown in Figure 7(a), while the corresponding root-mean-square fluctuation functions $F_d(\tau)$ of the DFA technique versus time scale $\tau$ (in days), are depicted in Figure 7(b).
Figure 6. Local slopes of the $\log F_d(\tau)$ vs. $\log \tau$ (10-base logarithms) calculated within a window of 18 points (dashed grey line), of 12 points (solid thin black line) and of 15 points (dashed black line) for the detrended and deseasonalised time series of (a) CO$_2$ daily power and (b) NO daily power. The error bars indicate the corresponding $1.96 \cdot s_a$ – intervals of the slopes over all the considered scales.

Figure 7. (a) The empirically derived infrared energy budget of the thermosphere from 1947 to 2016. The initial temporal march of the CO$_2$ (black line) and NO (grey line) daily power. (b) The corresponding root-mean-square fluctuation functions $F_d(\tau)$ of the DFA versus time scale $\tau$ (in days), in log-log plot and the respective best fit equations (CO$_2$: $y = 1.40x - 2.31$ with $R^2 = 0.998$, NO: $y = 1.43x - 2.54$ with $R^2 = 0.998$).

The derived DFA scaling exponent for the initial time series of CO$_2$ (NO) daily power (from 1947 to 2016) was found $a = 1.4 \pm 0.01$ ($a = 1.43 \pm 0.01$), assuming again long-range persistence. The algebraically (power law) fit gave better results than the exponential one for the power spectral density of both data sets (Figure 8(a,b)). Also, the local slope $a$ vs. $\log \tau$ (in 3 different window sizes of 24, 22 and 15 points) seemed to fluctuate again without any interval of constancy for both data sets (Figure 9(a,b)).
Figure 8. Power spectral density for the initial time series of (a) CO₂ daily power and (b) NO daily power (from 1947 to 2016), with the corresponding power-law (grey dashed line) and the exponential (grey solid line) fit (CO₂: $y = 2.19 \cdot 10^{-8} x^{-1.29}$ with $R^2 = 0.42$ and $y = 8.86 \cdot 10^{-7} e^{0.67x}$ with $R^2 = 0.20$, NO: $y = 1.55 \cdot 10^{-8} x^{-1.17}$ with $R^2 = 0.39$, $y = 4.43 \cdot 10^{-7} e^{-5.5x}$ with $R^2 = 0.18$).

Figure 9. Local slopes of the $\log F_d(\tau)$ vs. $\log \tau$ (10-base logarithms) calculated within a window of 24 points (dashed grey line), of 22 points (solid thin black line) and of 15 points (dashed black line) for the initial time series of (a) CO₂ daily power and (b) NO daily power (from 1947 to 2016). The error bars indicate the corresponding $1.96 \cdot s_a$ – intervals of the slopes over all the considered scales.

Our final step was to re-apply the above described analysis on the detrended and deseasonalised time series of CO₂ and NO daily power, for the period 1947-2016. Table 1 illustrates the best fit equations of the DFA technique and the results of both criteria proposed in [36]. Thus, it seemed again that long-range correlations of power-law type are not established either for CO₂ or for NO daily power time series (empirically derived from the infrared energy budget of the thermosphere from 1947 to 2016).
Table 1. DFA, power spectral density and local slopes applied on the detrended and deseasonalised time series of CO$_2$ and NO daily power, for the period 1947-2016.

| Method          | Exponential and Power-law fit on the power spectral density | Local slope $a$ decreases without any interval of constancy |
|-----------------|-------------------------------------------------------------|-----------------------------------------------------------|
| CO$_2$          | $y = 1.39x - 2.31$ with $R^2 = 0.997$                      |                                                            |
|                 | crossover at 5 months                                       |                                                            |
|                 | $y = 0.38x - 0.08$ with $R^2 = 0.94$                       |                                                            |
| NO              | $y = 1.22x - 2.34$ with $R^2 = 0.996$                      |                                                            |
|                 | crossover at 5 months                                       |                                                            |
|                 | $y = 0.26x - 2.34$ with $R^2 = 0.96$                       |                                                            |

4. Conclusions

1) In the present analysis we attempted to explore the temporal evolution of CO$_2$ and NO daily power, for the period 2002-2016. Although the derived DFA scaling exponent for the initial time series of both parameters assumed persistent behavior, power-law scaling and long range correlations were not established either for CO$_2$ or for NO daily power.

2) Similar results were extracted studying the scaling dynamics of the detrended and deseasonalised time series of CO$_2$ and NO daily power, for the period 2002-2016.

3) We also investigated the temporal march of the radiated CO$_2$ and NO daily power (empirically derived from the infrared energy budget of the thermosphere from 1947 to 2016). Although the derived DFA scaling exponent for the initial time series of both parameters assumed again persistent behavior, power-law scaling and long range correlations were established either for CO$_2$ or for NO daily power.

4) Similar results were extracted studying the scaling dynamics of the detrended and deseasonalised time series of CO$_2$ and NO daily power, for the period 1947-2016. The detection of the scaling properties of CO$_2$ and NO power time series may lead to more reliable prediction of the expected temperature decrease in the upper atmosphere, discussed in the recent scientific literature, which can potentially lead to substantial changes in the structure and composition of the atmosphere [37-41].

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