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Nitric oxide density enhancements due to solar flares

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Abstract

A differential emission measure technique is used to determine flare spectra using solar observations from the soft X-ray instruments aboard the Thermosphere Ionosphere Mesosphere Energetics Dynamics and Solar Radiation and Climate Experiment satellites. We examine the effect of the solar flare soft X-ray energy input on the nitric oxide (NO) density in the lower thermosphere. The retrieved spectrum of the 28 October 2003 X18 flare is input to a photochemical thermospheric NO model to calculate the predicted flare NO enhancements. Model results are compared to Student Nitric Oxide Explorer Ultraviolet Spectrometer observations of this flare. We present results of this comparison and show that the model and data are in agreement. In addition, the NO density enhancements due to several flares are studied. We present results that show large solar flares can deposit the same amount of 0.1–2 and 0.1–7 nm energy to the thermosphere during a relatively short time as the Sun normally deposits in one day. The NO column density nearly doubles when the daily integrated energy above 5 J m^{-2} is doubled.

Keywords: Nitric oxide; Soft X-ray irradiance; Solar flare; Thermosphere

1. Introduction

The presence of nitric oxide (NO) in the upper atmosphere was first suggested in 1945 when Nicolet recognized that solar ionizing radiation is absorbed in the thermosphere above 100 km (Nicolet, 1945). NO is a minor constituent of the thermosphere, however, it plays an important role in the energy balance of the thermosphere as it is a source of radiative cooling through infrared emissions. Barth et al. (1988) first hypothesized that solar soft X-rays were the source of low-latitude thermospheric NO and were the cause of thermospheric NO variability. Siskind et al. (1990, 1995) quantified the effects and demonstrated the need for improved measurements of the solar irradiance. SNOE measurements of both solar soft X-rays and thermospheric NO confirmed that soft X-ray irradiance between 0.1 and 7 nm is the primary low latitude source of NO production. The maximum effect is in the equatorial region at the subsolar point but it also influences the entire illuminated hemisphere (Barth et al., 2003). The density of NO reaches a maximum between 106 and 110 km, where the 0.1–7 nm irradiance is absorbed, and is highly variable as a function of time and latitude.

Solar soft X-rays are the primary energy driver for producing NO at low latitudes as they are a global source of energy that produce photoelectrons which dissociate molecular nitrogen, N_2, to produce excited atomic nitrogen, $N(^2D)$,

$$N_2 + e^* \rightarrow 2N(^2D,^4S) + e^*. \quad (1)$$

$N(^2D)$ then reacts with molecular oxygen, O_2, to produce NO,

$$N(^2D) + O_2 \rightarrow NO + O. \quad (2)$$

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Auroral electrons and energetic secondary auroral electrons provide the source of energy that leads to large amounts of NO at high latitudes. Far ultraviolet radiation near 190.8 nm (Barth, 1995) is the key mechanism that destroys NO through photodissociation,

$$NO + h\nu \rightarrow N(^4S) + O. \quad (3)$$

This reaction produces ground state nitrogen, $N(^4S)$, which goes on to further destroy NO through another chemical reaction,

$$NO + N(^4S) \rightarrow N_2 + O \quad (4)$$

thus enhancing the effectiveness of photodissociation for destroying NO and removing odd-nitrogen (Bailey et al., 2002). More complete discussions of NO production and loss mechanisms are described in Barth (1992) and Bailey et al. (2002).

Comparisons between SNOE observations and a photochemical model incorporating non-flare 0.1–7 nm solar irradiance showed good agreement (Barth and Bailey, 2004). During a solar flare the overall soft X-ray irradiance between 0.1 and 7 nm is increased, but the 0.1–2 nm region now dominates the spectrum, as compared to non-flare times where the 0.1–2 nm irradiance is a small contribution. The excess of 0.1–2 nm soft X-rays leads to more photoelectron production, which then leads to an increase in the low latitude NO density in this altitude region. In this paper we quantify the increase in low latitude NO density due to solar flare enhanced soft X-ray irradiance. Section 2 describes the method used to determine the solar flare soft X-ray irradiance and presents updated analysis and results from a previous paper. Section 3 describes SNOE measurements of NO and detailed observations of one solar flare. Section 4 describes the thermospheric photochemical model used to calculate the NO density enhancement and the comparison of model results to SNOE NO data observations. Section 5 describes the NO density enhancements due to several flares and the comparison to GOES-10 and XPS flare irradiances. Section 6 provides a summary, conclusions and suggestions for future work.

2. Solar flare soft X-ray irradiance

Rodgers et al. (2006) (hereafter referred to as Paper 1) presented a solar flare spectral analysis algorithm used to retrieve flare spectra from the Thermosphere Ionosphere Mesosphere Energetics Dynamics Solar EUV Experiment (TIMED) satellite X-ray ultraviolet XUV Photometer System (XPS) solar flare observations. The algorithm first uses the 'Differential Emission Measure' (DEM) technique for describing solar irradiance as presented by Warren et al. (1998) and earlier developed by Pottasch (1963). The flare spectrum is then determined by interpreting the XPS broadband measurements with a model that calculates theoretical spectra from DEMs input to this model. The model calculates the radiance of a solar emission line by convolving the DEM (unknown line-of-sight electron density of emitting hot plasma) with a function (containing assumed properties of the solar atmosphere) related to the emissivity of the atomic transition producing that emission (Warren et al., 2001). The solar emission line radiance is then used to calculate the full-disk solar irradiance measured at Earth from an optically thin emission line. Next, the solar irradiance is convolved with the XPS photodiode detector sensitivities to produce a model signal for each XPS detector channel. The initial DEM profile is iterated until a solar flare spectrum is produced that reproduces the observed XPS photodiode detector signals.

Since the publication of Paper 1, Solar Radiation and Climate Experiment (SORCE) satellite observations of very large flares that occurred during a 2-week period in the fall of 2003 were included in the flare spectral analysis to supplement SEE XPS observations. The SORCE XPS is nearly identical to the SEE XPS instrument. SORCE solar observations were made when Geostationary Operational Environmental Satellite (GOES)-8 observations were no longer available; therefore, GOES-10 observations and this satellite's transfer function have been used for analysis since the publication of Paper 1. No algorithm changes were made since the publication of Paper 1. Presented here are updated analysis and results from Paper 1.

Fig. 1 shows the calculated XPS 0.1–0.8 nm irradiances compared to the observed GOES-10 X-ray Sensor (XRS) 0.1–0.8 nm irradiances for 118 solar flares. The solid line represents perfectly matched XPS and XRS results. The calculated irradiances of dimmer M-class and C-class flares are in good agreement with the observed irradiances. Results for brighter M-class and X-class flares are in less agreement with calculated irradiances up to a factor of 2 less than the GOES observed irradiances. Agreement between XPS and GOES 0.1–0.8 nm irradiances is good considering the short lived nature of flares and that the XPS rarely observed the peak irradiance of the flares (Rodgers et al., 2006). This agreement provides confidence that

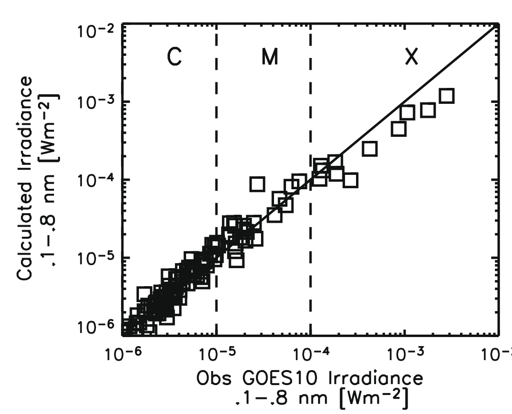

Fig. 1. The calculated XPS 0.1–0.8 nm irradiance compared to the GOES-10 0.1–0.8 nm irradiance observed at the time of the XPS observation. The calculated irradiances of dimmer M-class and C-class flares are in good agreement with the observed irradiances. Results for brighter M-class and X-class flares are in less agreement with calculated irradiances that are up to a factor of 2 less than the GOES observed irradiances.