Influence of solar variability on the infrared radiative cooling of the thermosphere from 2002 to 2014

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Abstract Infrared radiative cooling of the thermosphere by carbon dioxide (CO2, 15 μm) and by nitric oxide (NO, 5.3 μm) has been observed for 12 years by the Sounding of the Atmosphere using Broadband Emission Radiometry (SABER) instrument on the Thermosphere-Ionosphere-Mesosphere Energetics and Dynamics satellite. For the first time we present a record of the two most important thermospheric infrared cooling agents over a complete solar cycle. SABER has documented dramatic variability in the radiative cooling on time scales ranging from days to the 11 year solar cycle. Deep minima in global mean vertical profiles of radiative cooling are observed in 2008–2009. Current solar maximum conditions, evidenced in the rates of radiative cooling, are substantially weaker than prior maximum conditions in 2002–2003. The observed changes in thermospheric cooling correlate well with changes in solar ultraviolet irradiance and geomagnetic activity during the prior maximum conditions. NO and CO2 combine to emit 7 × 10^18 more Joules annually at solar maximum than at solar minimum.

1. Introduction

The Sounding of the Atmosphere using Broadband Emission Radiometry (SABER) instrument [Russell et al., 1999; Mlynczak, 1997] on the NASA Thermosphere-Ionosphere-Mesosphere Energetics and Dynamics (TIMED) satellite in late January 2014 marked 12 years of continuous observations of the atmosphere from the tropopause up to the middle thermosphere. In particular, SABER has provided continuous observations of the infrared cooling rates in the lower and middle thermosphere (100 to as high as 300 km altitude) due to emission from the vibration-rotation bands of carbon dioxide (CO2, 15 μm) and nitric oxide (NO, 5.3 μm). These data represent the first continuous, global observations of the two major radiative cooling mechanisms of the thermosphere over a nominal complete solar cycle.

Radiative cooling by CO2 and NO depends primarily on three factors: the kinetic temperature, the atomic oxygen abundance, and the abundance of NO or CO2. In the thermosphere, excitation of the vibrational modes of each molecule occurs largely by collisions with atomic oxygen (O) [Crutzen, 1970; Kockarts, 1980]. The vibrationally excited molecules may then radiate spontaneously or may be quenched, again largely due to collisions with O. The rate of collisional excitation depends on the product of the O abundance and the NO or CO2 abundance. Collisional excitation is also strongly temperature dependent and is proportional to exp(−E/kT), where E is the upper state energy, k is Boltzmann’s constant, and T is the kinetic temperature. Variations in cooling are thus linear in O, NO, or CO2, and nonlinear in temperature. The O and NO abundances are sensitive to variations in solar irradiance and to geomagnetic effects, the latter of which can be quite substantial for NO. In addition, CO2 is expected to be steadily increasing due to anthropogenic activity. Above 100 km the radiative transfer for both CO2 and NO is effectively optically thin and any emitted radiation escapes either to space or to the lower atmosphere.

The fine structure line of atomic oxygen at 63 μm also contributes to the radiative cooling of the thermosphere [Bates, 1951]. The temperature dependence of cooling by O at 63 μm is proportional to exp(−228/T). Consequently, infrared cooling by O changes very little even with large changes in temperature because of the relatively small argument (i.e., small energy at 63 μm) in the exponential [Mlynczak et al., 2005]. This letter therefore concentrates on the substantial observed variations in cooling by NO and CO2 made by the SABER instrument.
SABER commenced scientific operations in January 2002 after a successful launch into orbit on the TIMED spacecraft in December 2001. During the last 12 years SABER has chronicled the effects of solar variability on the infrared radiative cooling of the thermosphere on a variety of time scales. The large increases in radiative cooling of the thermosphere in response to coronal mass ejections and particle precipitation, now referred to as the natural thermostat effect, were documented early in the SABER mission [Mlynczak et al., 2003, 2005].

Prior to SABER observations, the response of the thermosphere to particle precipitation has been extensively studied [e.g., Gérard and Barth, 1977; Siskind et al., 1989]. Subsequent to these initial SABER observations, Mlynczak et al. [2007] documented the decrease in the radiative cooling by NO associated with the start of the declining phase of solar cycle 23. Short-term periodic features corresponding to the first four harmonics of the 27 day solar rotation period were observed in the radiative cooling by NO during solar minimum [Mlynczak et al., 2008, 2010a]. High-speed solar wind streams emanating from multiple coronal holes in the Sun’s atmosphere caused these features. Although not shown in this paper, these short-term periodic features have not reappeared from 2009 to 2013. Mlynczak et al. [2010b] further documented the occurrence of solar minimum and demonstrated that cooling by CO₂ dominates the radiative cooling of the thermosphere at that time. Hunt et al. [2011] noted the onset of solar cycle 24 as evidenced by increasing rates of radiative cooling by both NO and CO₂ simultaneously with increasing rates of solar activity.

In this paper we present the continuous 12 year SABER record of radiative cooling of the thermosphere and discuss the effects of solar variability now fully evident in this unique data set. Our intent is to document, for the first time, a complete record of thermospheric infrared cooling by NO and CO₂ over a nominal complete solar cycle. Solar cycle 23 is noted for the protracted length of its minimum. Solar cycle 24 is now being studied for its relative weakness compared to prior solar cycles. Concurrent observations of changes in solar ultraviolet irradiance and in geomagnetic activity also correlate with the observed changes in cooling and are discussed below.

The next section briefly discusses the methodology used to derive radiative cooling rates from the SABER limb radiance measurements at 5.3 μm and 15 μm. Results are presented in section 3 and a summary and discussion are given in section 4. The new Version 2.0 of the SABER data set is used in this letter.

2. Methodology

The SABER instrument is an infrared radiometer that records vertical profiles of limb radiance in 10 distinct spectral channels. From these data, vertical profiles of kinetic temperature, atmospheric composition, and rates of radiative cooling by NO and CO₂ are derived. Mlynczak et al. [2010b] describe this process in detail. The thermospheric cooling rate profiles are in units of nW/m³ (as opposed to K/d) because SABER does not measure atmospheric density over the depth of the thermosphere. These vertical cooling rate profiles can be integrated with respect to altitude and then with respect to latitude and longitude to compute the total infrared power (W) radiated by NO and by CO₂ over the entire Earth on a given day. To illustrate the influence of the solar cycle, we will use time series of both the daily global infrared power and the global annual mean cooling rate profiles over the last 12 years.

3. Results

3.1. Daily Global Power

We begin by showing the daily time series of global infrared power (W) radiated by NO and CO₂ for the past 12 years in Figure 1. The time series covers 22 January 2002 through 11 March 2014, over 4400 days of data. The smooth blue curve is the 60 day running mean of the daily data. SABER observes all local times over 60 days as a consequence of the 74° inclined orbit of the TIMED spacecraft. The 11 year solar cycle is visually evident in the data, with maximum emission in 2002, minimum in 2008/2009, and rising into the current maximum extending from 2011 to the present (March 2014). The deep minimum in cooling by NO is evident as the radiated power decreases by nearly an order of magnitude from 2002 to 2008. The increase in both NO and CO₂ cooling at the onset of solar cycle 24 is evident early in 2011 [Hunt et al., 2011]. Both the NO and CO₂ data exhibit high frequency “spikes” in cooling which are the result of geomagnetic activity [Mlynczak et al., 2003] and possibly solar flare events. The CO₂ cooling exhibits periodicities corresponding to the first three harmonics of the annual cycle [Mlynczak et al., 2008]. These longer periods in CO₂ are...
suggestive of forcing from the lower atmosphere weather. The 60 day running mean curves for both NO and CO₂ clearly indicate that the current maxima conditions of solar cycle 24 are substantially weaker than the prior maximum conditions in 2002–2003. Peak CO₂ emission in 2002 is about 15% larger than in 2011–2014, while peak NO emission is about 1.75 times larger.

As discussed in Mlynczak et al. (2010b), the primary driver of changes in CO₂ cooling over the solar cycle is changes in temperature, although CO₂ increases over the 12 years likely contribute as well. Changes in both temperature and NO abundance drive the changes in NO cooling over the solar cycle. Variability or changes in atomic oxygen may also influence both NO and CO₂ cooling rates. Temperature and composition changes in turn are driven by changes in solar irradiance and by geomagnetic activity that enhances auroral energy deposition and that drives composition changes in the thermosphere [e.g., Richards, 2004].

This time series of daily global radiated power has proven to be a very powerful tool to examine the response of the atmosphere to short-term variability of the Sun. In particular, the data are now being used to diagnose problems with forecasting geomagnetic storm intensity [Knipp et al., 2013] and to study effects of corotating interaction regions on the ionosphere [Verkhoglyadova et al., 2013].

To further investigate the influence of solar variability, we have computed the deseasonalized NO and CO₂ power since the beginning of the mission. The time series of NO and CO₂ cooling are deseasonalized as follows. Every 60 days, the TIMED spacecraft is rotated 180° about its yaw axis to maintain thermal stability. The mean global power is computed for NO and CO₂ for each spacecraft yaw cycle (which is also the time required to precess through all local times), with 6 yaw cycles in each "yaw year." The yaw cycle repeats...
annually from mid-January in one year to mid-January in the next. This results in 72 (12 years by 6 cycles per year) 60 day global means. Next the average power of the first yaw cycle in each year is computed, followed by the average power of the second yaw cycle, then the average of the third yaw cycle, etc. This gives six mean powers (over 12 years), one for each of 6 annual yaw cycles. The mean power is subtracted from the corresponding individual yaw cycle average power for each of the 12 years, i.e., the mean of yaw cycle 1 from each of the 12 first yaw cycles, and so forth, resulting in the deseasonalized NO and CO2 powers shown in Figures 2 and 3. For each 60 day period we also computed the difference between the mean ultraviolet solar irradiance measured by the Solar EUV Experiment (SEE) instrument [Woods et al., 2005] on the TIMED satellite and the long-term mean. A similar calculation is also performed for the Kp index. The spectral interval chosen for the SEE data is 1–190 nm that includes the Lyman-alpha line and the Schumann-Runge continuum that heat the lower thermosphere.

The results are shown in Figure 2 for CO2 and the SEE irradiance. In this figure we clearly see the progression of the solar cycle in the CO2 power (green bars) from January 2002 to January 2014. A peak in deseasonalized power occurred in late 2011, corresponding to a peak in the deseasonalized SEE irradiance. Additional, larger peaks in CO2 emission occurred in early and late 2013. In a similar way Figure 3 shows the deseasonalized NO power and the anomalies in the 60 day mean Kp index relative to the long-term mean of the Kp index. The deseasonalized NO power also shows a peak in late 2011 and two peaks in 2013 that correspond to the peaks in CO2 power. The visual correlation between SEE and CO2 emission and Kp and NO emissions is much higher during the stronger solar maximum conditions of 2002–2003 than those observed between 2011 and 2014. These data can also be used to compute the difference in infrared energy emitted by NO and CO2 at different times. In 2002 NO and CO2 combined to radiate $7 \times 10^{18}$ more Joules of infrared energy than in 2013, with each gas accounting for about one half of the total difference.
3.2. Global Annual Mean Cooling Rate Profiles

The daily infrared radiative power results above have proven extremely useful in studying the influence of the variable Sun on the Earth’s thermosphere. However, the power data offer no information on the variability as a function of altitude. For this purpose we present in Figures 4 and 5 the time series of the difference between the global annual mean cooling rate profile in 2002 and that observed each year from 2003 to 2013. Vertical profiles of the differences in cooling (nW/m²) are shown as a function of yaw year. Figure 4 indicates that the NO cooling rates decreased until the middle or latter part of 2008 and then began increasing until 2012, when they appear to level off through 2013. Figure 5 shows the difference in the vertical profile of global annual mean radiative cooling by CO₂ from that observed in 2002. Again, negative values indicate lower radiative cooling than in 2002. As with the NO cooling, the maximum change occurs in the middle to latter part of 2008 but at a much lower altitude of about 105 km. The cooling rates by CO₂ decreased by 25%–30% at the peak altitude from those observed in 2002. In contrast, the NO cooling rates decreased by more than 85% at the altitude of peak change. The CO₂ cooling also appears to level off in 2012–2013 similar to NO.

4. Summary and Discussion

We have presented 12 years of radiative cooling data associated with NO and CO₂ in the Earth’s lower and middle thermosphere. The influence of the variability of the Sun during solar cycle 23 and the first part of solar cycle 24 are evident in these data. A long and deep solar minimum previously noted is now observed in its entirety, and solar maximum conditions that are substantially weaker than the prior maximum conditions are now occurring. The deseasonalized vertically integrated cooling rates (radiated power) appear to be more strongly correlated with changes in solar ultraviolet irradiance and geomagnetic activity during the prior maximum than during the current maximum conditions. The influence of solar variability is evident in both NO and CO₂ cooling throughout the entire depth of the lower and middle thermosphere.

The SABER radiative cooling data for NO and CO₂ constitute a unique climate data record for testing upper atmosphere models in terms of both radiative/chemical physics and response to solar variability. One key application would be to the ongoing debate [e.g., Solomon et al., 2013] regarding the causes and consequences of the last solar minimum in 2008–2009 during which record low thermospheric densities occurred [Emmert et al., 2010]. Solomon et al. [2011] attributed the low density to changes in solar ultraviolet irradiance, while Emmert et al. [2010] conclude that other factors including composition changes must play a role. The SABER radiative cooling data can be used to test different scenarios on composition (atomic oxygen) changes, temperature changes, and CO₂ changes to further resolve this enigma.
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