Simulations of Airglow Variations Induced by the CO₂ Increase and Solar Cycle Variation From 1980 to 1991

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Abstract

Airglow intensity and Volume Emission Rate (VER) variations induced by the increase of CO₂ gas concentration and F10.7 variation (used as a proxy for the 11-year solar cycle variation) were investigated for the period of 1980 to 1991, encompassing a full solar cycle. Two airglow models are used to simulate the induced variations of O(¹S) greenline, O₂(0,1) atmospheric band, and OH(8,3) airglow for this study. The results show that both the airglow intensities and peak VERs correlate positively with the F10.7 solar cycle variation and display a small linear trend due to the increase of CO₂ gas concentration. The solar-cycle induced airglow intensity variations show that O(¹S) greenline has the largest variation (~26%) followed by the O₂(0,1) atmospheric band (~23%) and then OH(8,3) airglow (~8%) over the 11 year timespan. The magnitudes of the induced airglow intensity variations by the increase of CO₂ gas concentration are about an order of magnitude smaller than those by the F10.7 solar cycle variation. In general, the F10.7 solar cycle variation and CO₂ increase do not seem to systematically alter the VER peak altitude of the airglow emissions, though the OH(8,3) VER peak altitude moves up slightly during the years when the F10.7 value falls under 100 SFU.

Keywords: OH nightglow, O₂(0,1) atmospheric band, O(¹S) greenline, solar variation, F10.7, CO₂ variation

1. Introduction

A lot of research has been done in the area of global warming and climate change in recent years, primarily because the impacts of global warming and climate change on our environment can be profound and the causes remain a hot topic for debate. The increase of anthropogenic gas emission and solar variations have been considered as leading causes for global warming. If global warming is caused by the former, we would expect a warming in the lower atmosphere and a cooling in the upper atmosphere [Roble and Dickinson, 1989]. If, however, it is caused by solar variations, we would expect warming or cooling in all layers of the atmosphere. That the atmosphere responds differently to these two causes presents a great opportunity for us to potentially identify the leading cause for the climate change.

Roble and Dickinson [1989] used a global-average one-dimensional model to study how the upper atmosphere would change in response to the changes of trace gases originating from the lower atmosphere. Their numerical simulation results show that there would be about a 10 K temperature decrease in the mesosphere and a 50 K temperature decrease in the thermosphere when both the CO₂ and CH₄ gas concentration levels are doubled. In addition to the cooling, the model also predicts gas concentration changes varying from a 30% to 50% decrease of N₂, O₂, and O at the 300 km altitude. Their study illustrates that the increase of CO₂ and CH₄ in the lower atmosphere could cause temperature decrease and concentration change in the upper atmosphere. In Huang and Kane [2013], they summarized and reviewed previous works on deducing long-term thermospheric density trends from satellite drag measurements. The satellite drag measurements have shown

that the number densities of gas species in the thermosphere display a decreasing trend embedded in the sinusoidal solar cycle variation.

It has been shown that airglow is very sensitive to atmospheric conditions like ambient temperature or the number densities of gas species reacting in the airglow chemistry [Huang and Hickey, 2008; Khomich et al., 2010]. Any change in the temperature or gas concentrations would cause variations in the airglow intensity. Airglow intensity is a quantity obtained from column integration of the airglow volume emission rate. Based on Roble and Dickinson's study, it can be inferred that airglow intensity would change in response to the increase of CO₂ gas concentration in the lower atmosphere. On the other hand, solar variations also affect atmospheric conditions like temperature and gas concentrations as well. Therefore, it is expected that airglow intensity would also change in response to solar variations. There have been quite a few studies on airglow intensity or airglow temperature variations caused by the 11-year solar cycles using airglow observations [Scheer et al., 2005; Azeem et al., 2007; Pertsev and Perminov, 2008; Beig et al., 2008; Das et al., 2011]; however, no definitive correlation has been established.

A previous study by Huang [2013] investigates airglow intensity variations induced by only the CO₂ gas concentration change for hypothetical cases where CO₂ gas concentration is doubled, halved, or increased by 10% in the middle atmosphere. The simulation results of the study show that the O(¹S) greenline intensity and its Volume Emission Rate (VER) are most suitable for global warming study primarily because the induced variations of airglow intensity or airglow VER each respond in the same fashion

within the altitude of interest, i.e., they both increase (decrease) in response to an increase (decrease) of CO_2 . As for the OH airglow and $\text{O}_2(0,1)$ atmospheric band, the study indicates that airglow intensity variations may give ambiguous results due to the fact that the responses of VERs to an increase of CO_2 gas concentration are altitude-dependent with regions of positive and negative changes. After column-integration of the VERs, the induced airglow intensity variations can go both ways. The study indicates that the change of CO_2 gas concentration could leave its mark on airglow or the VERs in the MLT region.

As discussed in Shepherd et al. [1997], airglow is very sensitive to global change. However, using airglow measurements to deduce the change by the increase of anthropogenic gas emissions presents some challenges that must be overcome before an accurate assessment can be done. They identified two main factors that lead to natural variability of airglow, one being solar variability and the other being dynamics. Other studies [Scheer et al., 2005; Azeem et al., 2007; Pertsev and Perminov, 2008; Das et al., 2011] also found that a lot of variability in airglow or airglow temperature measurements might be under the influence of dynamics, thus making it difficult to deduce the variations induced by the solar cycle effect or by the CO_2 gas concentration increase. The current study uses a numerical simulation approach to investigate mesospheric airglow response to the increase of CO_2 gas concentration and F10.7 solar cycle variation. The advantage of this approach is that one can do controlled runs, as is done here, to better assess the influence of each of the key parameters on the induced airglow intensity variations.

The current study looks at airglow intensity and VER variations of three airglow emissions, specifically, OH(8,3) airglow, O₂(0,1) atmospheric band, and O(¹S) greenline, induced by the increase of CO₂ gas concentration and the 11-year solar cycle variation from 1980 to 1991, encompassing a full solar cycle. The relative contribution to the induced airglow and VER variations by these two factors are also examined. The F10.7 index is used as a proxy for the solar cycle variation. Both the CO₂ gas concentration and F10.7 index data are obtained from measurements to be described more in the next section. An OH Chemistry Dynamics (OHCD) model [Huang and Hickey, 2007; 2008] and a Multiple-Airglow Chemistry Dynamics (MACD) model [Huang and George, 2014; Huang, 2015] are used to simulate the induced variations of airglow intensity and VER for this study.

The paper is organized as follows. The OHCD and MACD models and data sources for CO₂ gas concentration and F10.7 index are described in Section 2. Results are presented in Section 3. Discussion is in Section 4 and Conclusions are in Section 5.

2. The OHCD and MACD Models and Data Sources

The OHCD and the MACD model are the two-dimensional, nonlinear, time-dependent chemistry dynamics models for the OH airglow and for the O₂ atmospheric bands and O(¹S) greenline, respectively. Both models have been previously used primarily for the investigation of gravity wave-airglow interactions [Hickey et al., 2003; Huang and Hickey, 2007, 2008, 2012; Huang and George, 2014; Huang, 2015]. In this study, only

the airglow chemistry part of the models is used for the simulations because the wave dynamics effects are not germane to the focus of the study, and thus they are not included. The chemical sets for the airglow emissions can be found in the aforementioned studies. Huang and George [2014] discussed that the branching ratios (ε and α) for the three-body recombination reaction affect the production of $O_2(b)$ and $O(^1S)$ species. The values they used for the airglow emissions were in line with the $O(^1S)$ greenline values published in the literature but not with the O_2 atmospheric bands. In this study, most of the rate coefficients in the MACD model are adopted except for the branching ratio ε , where a value of 0.26 is used instead to better match the values of the O_2 atmospheric bands.

The CO_2 gas concentration (in ppm) measured in Mauna Loa from 1980 to 1991 are obtained from the NOAA website (<http://www.esrl.noaa.gov/gmd/ccgg/trends/>). The F10.7 index values in Solar Flux Unit (SFU) are taken from the NASA website (<http://omniweb.gsfc.nasa.gov/form/dx1.html>), and they are used as a proxy for the 11-year solar cycle variation. For the current study, we focus on the time period from 1980 to 1991 that covers a full solar cycle with a decreasing and an increasing phase. Both the CO_2 gas concentration and F10.7 data are further averaged to produce yearly average data points.

Initial profiles of major gas species, atomic oxygen and hydrogen, and atmospheric temperature for latitude 18 N and longitude 290 E are obtained from the MSIS-90 model [Hedin, 1991], where the solar cycle variation of the atmospheric parameters and

temperature is from the solar cycle variation of F10.7 data. Initial profiles of minor gas species except for the atomic oxygen and hydrogen reacting in the airglow chemistries are obtained from the OHCD and MACD models. To deduce the change of the atmospheric gas concentrations and temperature brought about by the increase of the CO₂ gas concentration, the following describes the procedure. Figure 2 of Roble and Dickinson [1989] displays simulation results of atmospheric gas concentration percent change and temperature change as a function of altitude for the cases when the anthropogenic gas concentrations are doubled or halved. Based on their results for the case when the anthropogenic gas concentrations are doubled, an analytical expression for each gas species' fractional change and temperature change is found as a function of altitude from 70 km to 130 km, the altitude range employed in the OHCD and MACD models. The expressions are listed in Table 1 for major gas species (N₂ and O₂), temperature (T), and minor species (O, O₃, and H). When finding the analytical expressions for the changes, it is the values in the airglow region (80-100 km) that one tried to get the best fit from the analytical expressions. Overall, the analytical expressions fit the Roble and Dickinson's results quite well in the altitude range of interest. The plot of the CO₂ gas concentration as a function of year on the NOAA website has shown that it increases steadily over the past several decades. With a linear scaling on the analytical expressions using the data of annual CO₂ gas concentration change, these expressions are rescaled and coded in the OHCD and MACD models to allow for the gas species concentration change and temperature change brought about by the increase of CO₂ gas concentration on a yearly basis. Then what airglow intensity (integrated from 70 to 130 km) and VER variations would be induced by these two

factors (F10.7 solar variation and CO₂ gas concentration increase), separately or combined, are simulated.

3. Results

Following the procedure described earlier, the change of major and minor gas species' number densities and temperature in response to the CO₂ change in the airglow region in the Mesosphere and Lower Thermosphere (MLT) can be deduced. Since these quantities are a function of altitude, the results for 95 km altitude are shown as an example to illustrate how they change in response to CO₂ change. The percent change of number densities and temperature (axis on left) at 95 km altitude and CO₂ gas concentration percent change (axis on right) are shown as a function a year from Year 1980 to Year 1991 in Figure 1. The line with solid circles and upright solid triangles denote the percent change of major gases N₂ and O₂, respectively. As it shows, they both decrease at a rate of ~0.09% per year in response to the increase of CO₂ gas concentration. The line with solid squares denotes the percent change of the number density of O, which shows an increase at a rate of ~0.09% per year. The line with solid diamonds and the line with open squares denote the percent change of the number density of O₃ and H, respectively. O₃ shows an increase at a rate of ~0.05% whereas H shows a decrease at a rate of ~0.06% per year. The line with open diamonds denotes the decrease of temperature at a rate of ~0.025% per year. The line with open circles denotes the percent change of CO₂ gas concentration. The increase is almost linear except for the value in Year 1988, which shows a slightly larger increase. As such, the changes of the species also show a slightly larger change for the same year. With the increase of CO₂ gas

concentration, the number densities of O and O₃ show an increase and those of other species show a decrease accompanied by a decrease in temperature at 95 km altitude. With these parameters changing in the opposite directions, it is worth to look at how airglow responds to the atmospheric changes brought about by the increase of CO₂ gas concentration in addition to the changes brought about by the F10.7 solar cycle variation.

With that in mind, three scenarios are simulated for the investigation of airglow intensity and airglow VER variations induced by these two factors. The first scenario (labelled as S1) is to allow the F10.7 value to vary but keep the CO₂ gas concentration at the value in Year 1980. This allows one to see how airglow and its VER respond to the F10.7 solar cycle variation only. The second scenario (S2) is to allow the CO₂ gas concentration to increase but keep the F10.7 value fixed at the value in Year 1980. This allows one to isolate the effect induced by the increase of CO₂ gas concentration alone. The third scenario (S3) is to allow both the CO₂ gas concentration and F10.7 value to change, thus this scenario is more realistic and is what one would see the variations in airglow or VER caused by the combined effect of these two factors. When the F10.7 and/or CO₂ values are allowed to change, it is the yearly averaged values that are used in the models. Therefore, the simulation results of airglow intensity and airglow VER variations represent the yearly averaged values.

Figure 2 shows the results of the three scenarios for the O(¹S) greenline intensity as a function of year. The line with solid circles is for S1, the line with upright triangles is for S2, and the line with solid squares is for S3. From the figure, it can be seen that the

intensity variation for S1 and S3 both show a significant sinusoidal wave variation that tracks the F10.7 solar cycle variation. The magnitude of the largest variation is substantial ~25.9% for S1 and ~25.1% for S3, occurring in Year 1986 over the 11-year period. As for S2, the airglow intensity shows a linear increase and would have increased by 2.1% in Year 1991 due to the increase of CO₂ gas concentration alone. The effect of the CO₂ gas concentration increase on the O(¹S) greenline intensity is to increase the airglow intensity in rather small increments. Therefore, its effect can be significant only over a much longer period of time than what is considered here. As it shows in the figure, the O(¹S) greenline intensity values for S3 are a little bit larger than those for S1 and the difference increases slowly with time. The results reveal that solar cycle variation has a much larger influence on the O(¹S) greenline intensity and the intensity variation correlates positively with the solar cycle variation.

Figure 3 shows a similar plot but for the O₂(0,1) atmospheric band intensity as a function of year. The magnitude of the largest induced airglow intensity variation by the F10.7 solar cycle variation for S1 is about ~23.1% in Year 1986, and the airglow intensity variation shows a sinusoidal wave form as well. As for the induced airglow intensity variation by the increase of CO₂ gas concentration for S2, it also shows a linear increasing trend. The airglow intensity would have increased by 2.1% in 11 years. When examining the combined effect as for S3, the O₂(0,1) atmospheric band intensity shows the same feature as in Figure 2. The largest variation has a magnitude of ~22.3% occurring in Year 1986. The similar plot for the induced OH(8,3) airglow intensity variation is shown as a function of year in Figure 4. Again, the largest induced airglow

intensity variation ($\sim 7.6\%$ decrease) by the F10.7 solar cycle variation is seen in Year 1986 for S1, and the intensity variation also shows a sinusoidal wave form. The induced airglow intensity variation by the increase of CO_2 gas concentration, however, shows a linear decrease for S2 with a net 0.48% decrease in Year 1991. The combined effect as for S3 shows a sinusoidal wave form with the largest variation of 7.8% occurring in Year 1986. From Figures 2-4, it can be seen that the airglow intensity variations do track the F10.7 solar cycle variation with a small, slow linear trend that is due to the increase of CO_2 gas concentration. The $\text{O}(^1\text{S})$ greenline and $\text{O}_2(0,1)$ atmospheric band intensities show an increasing trend whereas the $\text{OH}(8,3)$ airglow intensity shows a decreasing trend. In general, the airglow intensity variations induced by the F10.7 solar cycle variation are about an order of magnitude larger than those induced by the increase of CO_2 gas concentration for the time period under study. Further, the $\text{O}(^1\text{S})$ greenline intensity has a larger induced variation than the $\text{O}_2(0,1)$ atmospheric band, and the $\text{OH}(8,3)$ airglow intensity has the smallest induced variation by the F10.7 solar cycle variation. The increase of CO_2 gas concentration induces a similar amount of intensity variation in $\text{O}(^1\text{S})$ greenline and $\text{O}_2(0,1)$ atmospheric band that is $\sim$ four times larger than the induced intensity variation in $\text{OH}(8,3)$ airglow.

The previous three figures all show a clear sinusoidal wave variation in airglow intensity induced by the F10.7 solar cycle variation. Next, airglow intensity variations in relation to the F10.7 solar cycle variation and F10.7 percent change are examined. The top plot in Figure 5 shows the $\text{O}(^1\text{S})$ greenline intensity (axis on left, the line with solid circles) and the F10.7 values (axis on right, the line with upright triangles) as a function of year. It

can be seen that the $O(^1S)$ greenline tracks, i.e., correlates positively with the F10.7 variation. Similar behavior is also seen in $O_2(0,1)$ atmospheric band (figure not shown) and $OH(8,3)$ airglow intensity shown in Figure 6. Similar plots but replacing F10.7 values with F10.7 percent change or replacing intensity variation with intensity percent change were plotted. It is found that the largest F10.7 percent decrease ($\sim 70\%$) occurs between Year 1985 and 1986, which coincides with the largest decrease of $O(^1S)$ greenline intensity. It is also found that the $O(^1S)$ greenline intensity percent change tracks the F10.7 percent change, not the F10.7 variation. Similar features are seen in $O_2(0,1)$ atmospheric band and $OH(8,3)$ airglow as well. The bottom plot in Figure 5 shows the $O(^1S)$ greenline intensity (axis on left, the line with solid circles) and the CO_2 gas concentration percent change (axis on right, the line with upright triangles) as a function of year. The plot shows clearly that $O(^1S)$ greenline intensity bears a linear relationship with the percent change of CO_2 gas concentration. The $O_2(0,1)$ atmospheric band shows the similar behavior as well. However, the bottom plot in Figure 6 shows that the $OH(8,3)$ airglow intensity correlates negatively with the percent change of CO_2 gas concentration.

Airglow intensity obtained from ground-based measurements is a result of column integration of airglow VER, thus it loses altitudinal information after integration. Therefore, the airglow intensity response to the CO_2 and F10.7 variations might not reflect what the VER response is to these forcings. Here, how the VER of these airglow emissions responds to these forcings is examined. The VER for each airglow emission can be deduced from the airglow chemical reactions. Listed below are the expressions

for the VER of O(¹S) greenline and O₂(0,1) atmospheric band (Huang and George [2014]), and for the VER of OH(8,3) airglow (Huang [2013]).

$$V_{O1S} = \frac{R_{17} R_3 R_7 [O]^3 [M]}{L_4 (R_{14} [O_2] + R_{15})} \quad (1)$$

$$V_{O_2(0,1)} = \frac{R_{16} [O]^2 [M]}{L_4 L_5} \{ R_2 L_4 + R_3 (R_4 [O_2] + R_5 [N_2] + R_6 [O]) \} \quad (2)$$

$$V_{OH} = \frac{R_8^{OH} R_6^{OH} [H] [O_3]}{R_8^{OH} + R_9^{OH} [O] + R_{10}^{OH} [O_2] + R_{11}^{OH} [N_2]}, \quad (3)$$

where $L_4 = R_4 [O_2] + R_5 [N_2] + (R_6 + R_7 + R_8) [O] + R_9$ and $L_5 = R_{10} [N_2] + R_{11} [O_2] + R_{12} [O] + R_{13}$.

The rate coefficients R_x^{OH} in V_{OH} can be found in Huang and Hickey [2008] and the rate coefficients R_x in V_{O1S} and $V_{O_2(0,1)}$ are from Huang and George [2014], where X refers to the chemical reaction listed in the tables in the aforementioned papers. The VER of O(¹S) greenline is proportional to the product of O number density cubed and major gas species' (M) number density, *i.e.*, $[O]^3 [M]$, but there are terms in the denominator that also include major gas species M and O. As for O₂(0,1) atmospheric band, the VER is proportional to the product of O number density squared and major gas species' number density, *i.e.*, $[O]^2 [M]$, and the terms in the denominator are as complicated as those for O(¹S) greenline. The VER of OH(8,3) airglow is proportional to the product of H number density and O₃ number density, $[H] [O_3]$, and inversely proportional to the sum of the terms involving O and major gas species M.

The peak VER of O(¹S) greenline (axis on left) and the F10.7 value (axis on right, the line with solid diamonds) are plotted as a function of year in the top plot of Figure 7 for the three scenarios. The line with solid circles denotes the peak VER value for S1, the

line with upright triangles denotes the peak VER value for S2, and the line with solid squares denotes the peak VER value for S3. From the figure, it can be seen that the peak VER of O(¹S) greenline tracks the F10.7 variation when the F10.7 value is allowed to change (S1 and S3) and it increases linearly with the increase of CO₂ gas concentration when only the CO₂ gas concentration is allowed to change (S2). When both factors are allowed to change (S3), the combined effect on the peak VER is that the VER value tracks the F10.7 solar cycle variation and slightly increases with time. So the O(¹S) peak VER's response to these two factors is the same as the O(¹S) greenline intensity. The largest decrease of the VER occurs in Year 1986 with a magnitude of 27% and 26.2% for S1 and S3, respectively. The net increase for S2 is ~2.1% in Year 1991. The peak altitude of the VER is also examined and plotted in the bottom plot of Figure 7 for the three scenarios. It can be seen from the figure that the peak altitude of the O(¹S) greenline VER for S1 remains at the same altitude at 95.6 km except for Year 1990. Note that when examining the data of the O(¹S) peak VER, it is found that it peaks at both 95.6 and 95.5 km altitudes for Year 1990. The lower altitude is picked to show in the figure to not miss any possible feature. The VER peak altitude for S2 shows a 0.1-km lower in altitude in Year 1990 and 1991. It is also found that the peak VER peaks at both 95.6 and 95.5 km altitudes in Year 1990, but it peaks only at one single altitude at 95.5 km in Year 1991. As for S3, the peak VER is found to be lowered by 0.1 km from Year 1989 to Year 1991. Although the results seem to suggest that the VER peak altitude might be affected by either F10.7 solar variation or the increase of CO₂ gas concentration, we would be hesitant to jump to that conclusion just yet. The reason is that a 0.1-km vertical grid is used in the models and so the vertical resolution of the results can only

attain 0.1 km. Therefore, it is possible that the height variation seen in the last three years might be nothing more than just the fluctuation within the ± 0.1 km uncertainty.

The peak VER and peak VER altitude of $O_2(0,1)$ atmospheric band are plotted as a function of year in the top and bottom plot of Figure 8, respectively. From the top plot, it can be seen that the peak VER of $O_2(0,1)$ atmospheric band for S1 (denoted by the line with solid circles) and S3 (denoted by the line with solid squares) track the F10.7 solar cycle variation with the latter slightly larger than the former due to the CO_2 increase. The largest decrease of the VER is $\sim 25.2\%$ for S1 and $\sim 24.3\%$ for S3 occurring in Year 1986. While for S2 (denoted by the line with upright triangles), the peak VER shows a small linear increase with a net increase of $\sim 2.4\%$. When examining the peak VER altitude for the three scenarios in the bottom plot of Figure 8, it can be seen that the peak VER altitude does not change at all for all three scenarios for the time period considered. Similar plots for the $OH(8,3)$ airglow VER and its peak altitude for the three scenarios are shown in Figure 9. As the figure shows, the VER also responds to these forcings similar to its airglow intensity response. The largest decrease is about $\sim 8.7\%$ for S1 (denoted by the line with solid circles) and $\sim 8.8\%$ for S3 (denoted by the line with solid squares), both occurring in Year 1986. The VER for S2 (denoted by the line with upright triangles) shows a small decreasing trend and is decreased by 0.2% in 11 years. As for the VER peak altitude, we can see in the bottom plot of the figure that there is no change for S2. However, it moves up 0.1 km from Year 1984 to Year 1987 for S1 and S3. As mentioned earlier, the vertical resolution is subject to ± 0.1 km uncertainty. Therefore, it should be stressed again that the 0.1-km increase may be nothing more than just the result

of fluctuating uncertainty. That being said, it is interesting to note that the F10.7 values all fall below 100 SFU during these four years. So it is possible that the peak altitude of the OH(8,3) VER might change due to different solar conditions, and the results indicate that it moves up when the F10.7 goes below certain values. More work needs to be done to include more solar cycles to make a better assessment of this conjecture.

4. Discussion

Several marked differences are noted in the following when comparing the current study to the study by Huang [2013]. First of all, Huang [2013] investigates airglow intensity and VER variations induced by *only* the CO₂ variation and for hypothetical cases, i.e., when CO₂ is doubled, halved, or increased by 10%. In this study, airglow and VER peak altitude response to solar cycle variation are investigated in addition to the increase of CO₂ gas concentration. Both studies use linear scaling on the gas species and temperature change induced by the CO₂ variation based on the results of Roble and Dickinson [1989]. However, changes induced by the CO₂ variation were assumed to be constant in the airglow region in Huang [2013] whereas the induced changes, which are a function of altitude, have each been properly represented with an analytical expression (see Table 1) in this study. Both studies use the OHCD and MACD models to simulate airglow and VER responses. However, the current study uses the MSIS-90 model as a reference model for initial gas species and temperature, whereas Huang [2013] used the MSIS-90 as a reference model for temperature and most of the species except for atomic oxygen and hydrogen where the observational data were used. Comparing the results of induced airglow variations by the increase of CO₂ gas concentration, both studies reveal

that the induced airglow variations can be substantial over several decades and its effect is to slowly change the baseline of airglow magnitude each year.

As this study shows, the induced airglow intensity and VER variations by the increase of CO₂ gas concentration is not really significant within the 11-year timespan. However, the effect by the increase of CO₂ gas concentration can be substantial over a longer time period because the historical data of the CO₂ gas concentration measurements have shown a steady increase. According to the current study, the airglow intensity level would have changed as well in response to the CO₂ change. One can extrapolate the airglow results to the present date to get a rough estimate on how much it would have changed. For example, the induced O(¹S) greenline intensity variation by the increase of CO₂ gas concentration shows a 2.1% increase in Year 1991 compared to the value in Year 1980. The induced airglow intensity variation would have increased by ~ 6.7% in Year 2015. This shows that the induced airglow intensity variation by the CO₂ gas concentration increase can be somewhat substantial over several decades. Therefore, care must be taken when it comes to data analysis on data sets that span many decades because there is a linear trend in the data that is due to the CO₂ gas concentration increase. Comparing the airglow intensity and VER variations induced by the F10.7 solar cycle variation to those induced by the increase of CO₂ gas concentration, it can be seen that the induced variations by the former are by far much larger than those by the latter. The induced airglow intensity variations by the F10.7 solar cycle variation can reach magnitudes similar to those induced by a small linear gravity wave [Huang and George, 2014]. The years under study encompass a solar minimum. It'd be worth

investigating what the induced variations would be when more solar cycles are included, which is planned for a future study.

In a previous work presented at a Long-term Changes and Trends workshop, the observational data of atomic oxygen and hydrogen from Garcia and Solomon [1985] were used in the OHCD and MACD models, and the same atomic oxygen data were used for the time period under study [Huang, 2014]. This is equivalent to suppressing the solar cycle variation of atomic oxygen in the models, which produces very different results. Here in Figure 10 shows an example of $O(^1S)$ greenline as a function of year from Huang [2014] so that readers can make a visual comparison of Figures 2 and 10. As can be seen from Figure 10 for S1 and S3, when solar cycle variation of atomic oxygen is omitted, the variation of $O(^1S)$ greenline intensity is very small, only about $\sim 0.2\%$ during the 11-year period for S1. The variation is about two orders of magnitude smaller than when the solar cycle variation of atomic oxygen is included. In addition, the variation for S1 in Figure 10 looks like a sinusoidal squared wave pattern whereas that in Figure 2 shows a sinusoidal wave pattern. The intensity variation for S1 in Figure 10 results from the solar cycle variation of major gas species and temperature. These marked differences also apply to the other two airglow emissions. This indicates that solar cycle variation of atomic oxygen plays an important role in the airglow intensity and VER variations.

The current study shows a $\sim 26\%$ variation of $O(^1S)$ greenline intensity, a $\sim 23\%$ variation of $O_2(0,1)$ atmospheric band intensity, and a $\sim 8\%$ variation of $OH(8,3)$ airglow intensity induced by the F10.7 solar cycle variation from 1980 to 1991. In addition to the rather

significant airglow intensity variations, the variations also track the F10.7 solar cycle variation. Wiens and Weill [1973] reported a 25% increase of OH airglow over a solar cycle. Scheer et al. [2005] found no correlation for the OH airglow and a possible positive correlation for the $O_2(0,1)$ atmospheric band with the F10.7 solar cycle variation based on their four-year worth of measurements at El Leoncito, Argentina from 1998 to 2002. On the other hand, Das et al. [2011] reported a significant variation $\sim 20\%$ of $O(^1S)$ greenline based on the observations at Kiso, Japan from 1979 to 1995. A recent study on the variability of OH(3-1) emission altitude using nighttime limb-view observations from 2003 to 2011 by the SCIAMACHY (Scanning Imaging Absorption spectroMeter for Atmospheric CHartographY) instrument onboard Envisat satellite shows that there are no obvious long-term trends or 11-year solar cycle signatures present in the OH emission altitude time series [von Savigny, 2015]. Additionally, Gao et al. [2016] analyzed 13 years of data of four nightglow emissions (NO emission at $5.3 \mu m$, O_2 infrared atmospheric band at $1.27 \mu m$, and OH emissions at 2.0 and $1.6 \mu m$) measured from the Sounding of the Atmosphere using Broadband Emission Radiometry (SABER) onboard the Thermosphere-Ionosphere-Mesosphere Energetics and Dynamics (TIMED) satellite. They reported that the global mean nightglow emissions were highly correlated with solar radiation and the OH nightglow peak altitudes did not show any obvious correlation to the solar radiation. Sivakandan et al. [2016] use the same data of OH emission at $1.6 \mu m$ from SABER to study long-term variation of the peak emission altitude and VER over the Indian section. Their analysis shows that the night time OH peak emission altitude seems to display a weak decreasing trend at a rate of ~ 20 m/year. A theoretical study by Grygalashvyly et al. [2014] on the OH layer trend shows that OH

layer peak altitude change due to the increase of anthropogenic gas emission is about ~ 2 m/year and the peak altitude change due to the 11-year solar cycle can be neglected. The simulations of nightglow intensity variation induced by the solar cycle variation in this study are in agreement with the Gao et al. study. The results of the OH(8,3) VER peak altitude tend to be in agreement with the von Savigny and the Gao et al. study if the 0.1-km change of peak altitude is due to the fluctuation of the uncertainty of the vertical resolution in the models. Again, more solar cycles are needed to determine if OH emission altitude remains at the same altitude for different solar conditions. Also note that the study by Gao et al. shows a positive correlation of O₂ infrared atmospheric band peak altitude with the solar radiation (0.51 ± 0.08 km/100 sfu) whereas the simulations of O₂(0,1) atmospheric band at $.864 \text{ } \mu\text{m}$ in this study do not show that. One possible reason for this discrepancy might be that the chemistry for the emissions is different.

Due to the different solar cycles and geophysical locations where the data were taken, not to mention the different time periods and methods used in the data analysis, it is difficult to make a direct comparison among these studies. Some of the previous studies attempted to find a linear trend from the solar cycle variations of either airglow intensity or temperature and expressed the trends per 100 sfu. This is equivalent to finding an average solar cycle effect [Scheer et al., 2005]. As shown in the plots in this study, the solar cycle effect on airglow intensities display a sinusoidal wave pattern. It is thus not surprising that previous studies show rather disparate results because the use of different lengths of data to extract the average solar cycle effect might by itself lead to different results.

In Huang and Hickey [2007] they investigated latitudinal variations of airglow species for three different latitudes. Their results showed that the overall behavior of the airglow species at the three latitudes is similar to one another, subject to minor differences. This study uses initial profiles of the major and minor gas species for latitude 18 N and longitude 290 E. It is expected that the main features of the results reported here apply to other geographical locations of different latitudes and longitudes if the number densities of gas species and temperature are similar to what is used in this study.

5. Conclusions

Airglow intensity and VER variations induced by the increase of CO₂ gas concentration and F10.7 solar cycle variation from Year 1980 to 1991 are simulated with an OHCD and a MACD model. The MSIS-90 model is used to obtain the initial profiles of major gas species, atomic oxygen and hydrogen, and atmospheric temperature, where their solar cycle variation is from the solar cycle variation of F10.7 data. The induced changes of gas species and temperature by the increase of CO₂ gas concentration are derived from a linear scaling of the results by Roble and Dickinson [1989] for the case when the anthropogenic gas concentrations are doubled. The OH(8,3) airglow, O₂(0,1) atmospheric band, and O(¹S) greenline are the three airglow emissions in the MLT region under the investigation. The main features of the results are summarized below.

- The simulation results indicate that airglow intensity responds to the F10.7 solar cycle variation a lot more than to the increase of CO₂ gas concentration for the

time period under study. In general, the airglow variations induced by the former are an order of magnitude larger than those induced by the latter.

- A sinusoidal wave variation is seen in the airglow intensity for all three airglow emissions. It is found that airglow intensity variations track (correlates positively with) the F10.7 solar cycle variation and display a small linear trend by the increase of CO₂ gas concentration.
- The airglow intensity variations induced by the F10.7 solar cycle variation show that O(¹S) greenline has the largest variation (~26%) followed closely by the O₂(0,1) atmospheric band (~23%), and then by the OH(8,3) airglow (~8%). These induced airglow variations are quite substantial that they should be detectable from measurements over a decade.
- The induced airglow intensity variations by the increase of CO₂ gas concentration shows a ~2% increase in O(¹S) greenline and O₂(0,1) atmospheric band, and a ~0.5% decrease in OH(8,3) airglow in 11 years. The trend in the OH(8,3) airglow intensity is negative and ~4 times smaller. The induced airglow intensity variations can be substantial over several decades.
- Regarding the peak VERs, it is found that these VERs also respond similarly like the airglow intensities, i.e., their variations track the F10.7 solar cycle variation and a linear trend due to the increase of CO₂ gas concentration; the magnitude of the variations by the former is also roughly an order of magnitude larger than that by the latter.
- Regarding the peak altitudes of VERs, it is found that the increase of CO₂ gas concentration overall has no effect on the peak altitudes of the VERs for the time

period under study. As for the influence of the F10.7 solar cycle variation on the peak altitudes, there is no effect on the $O_2(0,1)$ atmospheric band VER. But there might be a possible effect on the $O(^1S)$ greenline and the $OH(8,3)$ VER since the peak altitudes have slightly moved albeit at a magnitude within the models' vertical resolution. In general, the F10.7 solar cycle variation does not seem to systematically alter the VER peak altitude of the airglow emissions except for the peak altitude of the $OH(8,3)$ VER which shows a higher peak altitude during the years that had low F10.7 values less than 100 sfu.

The results of this study indicate that airglow emissions and their VERS in the MLT region do respond to these forcings (CO_2 and F10.7) in different ways. This study only looks at the airglow response for a time period of 11 years that encompasses a solar minimum in a solar cycle. Extending the study for a longer period of time that includes more solar cycles accompanied by the increase of CO_2 gas concentration is planned to better understand how airglow responds to these forcings over several decades.

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Figure Captions

Figure 1. The percent change of number density of gas species and temperature at 95 km altitude due to the CO₂ change (axis on left) and the CO₂ percent change (axis on right) as a function of year from 1980 to 1991. As it shows, N₂, O₂, T, and H decrease whereas O and O₃ increase when the CO₂ gas concentration increases.

Figure 2. O(¹S) greenline intensity as a function of year with three different scenarios. The line with solid circles denotes the first scenario – the CO₂ gas concentration is kept the same as the value in Year 1980 for all years and the F10.7 values are from the measurements. The line with upright triangles denotes the second scenario – the CO₂ gas concentration is from the measurements and the F10.7 values are kept the same as the value in Year 1980 for all years. The line with solid squares denotes the third scenario – both the CO₂ gas concentration and the F10.7 values are from the measurements.

Figure 3. Same as Figure 2 but for O₂(0,1) atmospheric band intensity.

Figure 4. Same as Figure 2 but for OH(8,3) airglow intensity.

Figure 5. The top plot shows the O(¹S) greenline intensity (axis on left, the line with solid circles) and the F10.7 value (axis on right, the line with upright triangles) as a function of year. The bottom plot shows the O(¹S) greenline intensity (axis on left, the line with solid circles) and the percent change of CO₂ gas concentration (axis on right, the line with upright triangles) as a function of year.

Figure 6. Same as Figure 5 but for OH(8,3) airglow intensity.

Figure 7. The top plot shows the peak value of the O(¹S) greenline VER (axis on left) and the F10.7 value (axis on right) as a function of year for the three scenarios. The bottom plot shows the peak altitude of the O(¹S) greenline VER (axis on left) and the F10.7 value (axis on right) as a function of year.

Figure 8. Same as Figure 7 but for O₂(0,1) atmospheric band.

Figure 9. Same as Figure 7 but for OH(8,3) airglow.

Figure 10. Same as Figure 2 but for the case when solar cycle variation of atomic oxygen was suppressed.

Table 1. Analytical expression for atmospheric species fractional change and temperature change as a function of altitude derived from Figure 2 of Roble and Dickinson [1989] for the case when the anthropogenic gas concentrations are doubled.

	Analytical expression	Altitude range, z (km)
N_2' / N_2	$7 \times 10^{-5} z^2 - 0.0192 z + 0.9954$	70-130
O_2' / O_2	$-0.01z + 0.7$ $-0.006z + 0.38$ $-0.009z + 0.6767$ -0.4	70-80 80.1-100 100.1-120 120-130
T'	$0.1543z - 24.414$	70-130
O' / O	$0.025z - 1.795$ 0.2 $-0.02z + 2.2$ -0.2	70-80 80.1-100 100.1-120 120.1-130
O_3' / O_3	$0.0072z - 0.454$ 0.1 $-0.244z + 24$ $-0.021z + 1.7$ -0.61	70-75 75.1-97.9 98-100 100.1-110 110.1-130
H' / H	$-0.03z + 2.41$ $-0.008z + 0.64$ $-0.0085z + 0.6767$ $0.0025z - 0.5233$	70-79.9 80-90 90.1-110 110.1-130

Figure 1

Number Density & Temperature Percent Change
Lat=18 N, Lon=290 E, Altitude=95 km

Figure 2

O(1S) Greenline Intensity
Lat=18 N, Lon=290 E

Figure 3

O2(0,1) Atmospheric Band Intensity

Lat=18 N, Lon=290 E

Figure 4

OH(8,3) Airglow Intensity
Lat=18 N, Lon=290 E

Figure 5

Variation of O(1S) Greenline and F10.7

Variation of O(1S) Greenline and CO2

Figure 6

Variation of OH Airglow and F10.7

Variation of OH Airglow and CO2

Figure 7

Variation of O(1S) Greenline Peak VER

Variation of O(1S) Greenline Peak VER Altitude

Figure 8

Variation of O2(0,1) Atmospheric Band Peak VER

Variation of O2(0,1) Atmospheric Band Peak VER Altitude

Figure 9

Variation of OH(8,3) Airglow Peak VER

Variation of OH(8,3) Airglow Peak VER Altitude

Figure 10

O(1S) Greenline Intensity
Lat=18 N, Lon=290 E