GLOBAL ANALYSIS OF TWILIGHT HYDROXYL AIRGLOW

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ABSTRACT

Latitudinal characterizations of twilight mesospheric hydroxyl volume emission rate (VER) from year 2002 to 2005, are made possible using the SABER (Sounding of the Atmosphere using Broadband Emission Radiometry) sensor, a ten-channel infrared radiometer onboard NASA’s TIMED (Thermosphere Ionosphere Mesosphere Energetics and Dynamics) satellite. Implementation of a binning algorithm over time and geography provides global twilight characteristics from SABER radiometric channel 9 data, centered at $\lambda = 1.64 \, \mu m$ for the OH (5,3) and OH (4,2) Meinel airglow band infrared emissions, and SABER radiometric channel 8 data, centered at $\lambda = 2.06 \, \mu m$ for the OH (9,7) and OH (8,6) emissions. The findings show an equatorial effect in both infrared radiometric channels. Faster rise rates are observed at sunset while slower fall rates are observed at sunrise near the equator when compared with rates calculated at midlatitudes. Both hydroxyl channels show the most distinct sunset equatorial effects in the year 2002, and the most distinct sunrise equatorial effects in the year 2005.

1. INTRODUCTION

The region composing the mesosphere, lower thermosphere, and ionosphere (MLTI) is an important region of the atmosphere for modeling the energy budget and resulting climatology of the Earth. The mission of the TIMED satellite is to extend previous atmospheric measurements using infrared sensors to obtain three-dimensional global measurements of the most important MLTI parameters over time, and thus validate and improve theoretical models of this important region of the atmosphere [1].

1.1. TIMED Satellite

On December 7, 2001, the TIMED satellite was launched from a Delta II launch vehicle at Vandenberg Air Force Base, CA. TIMED is equipped with four instruments, although the study reported herein will focus singularly on data gathered from one of the four. Instruments on board include SEE (Solar Extreme Ultraviolet Experiment), GUVI (Global Ultraviolet Imager), TIDI (TIMED Doppler Interferometer), and SABER [1].

The orbit of TIMED exhibits an inclination of 74.1° from the equator and is positioned at a distance from the Earth of 625 km, which is portrayed in fig. 1 [2]. The TIMED satellite orbits around the Earth an average of 14.84 times per day [1]. During these orbits, data from a comprehensive range of latitudes and longitudes are obtained by the SABER sensor onboard TIMED. In this way daily, seasonal, and annual trends in atmospheric activity can be obtained and monitored.

Fig. 1. Graphical portrayal of TIMED’s inclined orbit.
1.2. SABER Sensor

SABER is a ten-channel infrared radiometer that was engineered by the Space Dynamics Laboratory (SDL) at Utah State University and the NASA Langley Research Center (LaRC) [3]. Each of the ten channels is equipped with a bandpass filter centered on the emission frequencies corresponding to different atmospheric species. Figure 2 depicts an artist’s rendition of the SABER sensor with its ten channels. Due to the inclined orbit of TIMED, data gathered by SABER is restricted to latitudes between \( \pm 83^\circ \).

![Fig. 2. SABER instrument with 10 channels portrayed in their field of view positions.](image)

1.3. Photochemistry of MLTI Region

Solar radiation which dissociates atmospheric species produces optically-excited atoms and molecules. Photons emitted at specific frequencies allow scientists to characterize the species and the photochemical reactions taking place [4]. Excited hydroxyl molecules derive from reactions involving ozone, monatomic hydrogen and monatomic oxygen as follows:

\[
OH + O \rightarrow H + O_2, \quad (1)
\]

and

\[
H + O_3 \rightarrow O_2 + OH. \quad (2)
\]

OH airglow emissions are modeled by both vibration energies of excited hydroxyl molecules and rotational energy. These OH emissions are illustrated in fig. 3 [5], a spectrum of OH nighttime airglow observed from the ground at Poker Flat, Alaska in 1975. Each vibration quantum transition between energy states is labeled with a pair of numbers. The pair of numbers presented on each main vibrational airglow band correspond to Meinel vibrational energy states. These states have reference to energy levels of the excited hydroxyl molecules from (2). Transitions from one state to another make up the spectrum shown in fig. 3. Quantum level changes of \( \Delta \nu = 2 \) result in emissions in the near-infrared as observed by SABER. Figure 3 also depicts pass-band responses of radiometer channels 8 and 9 of SABER overlaid on the ground-based spectrum of the OH nighttime airglow.

![Fig. 3. Radiometer channels 8 and 9 bandpass filters superimposed on observed ground-based spectrum of the OH(\( \Delta \nu = 2 \)) infrared airglow emissions of the Meinel band sequence.](image)

1.4. Twilight Data Characteristics

Since the photochemistry of the mesospheric airglow is driven by the solar flux, large variations of airglow emissions are present between times before and after twilight. Due to the TIMED satellite’s inclined orbit of 74.1° from the equator, it is difficult for SABER to collect comprehensive data pertaining to a specific sunrise or sunset event. In the case where the satellite’s orbit remains in twilight for a significant amount of time, however, much data for that event are gathered. In all other cases, the instrument may receive a few scans of twilight observations during a day as TIMED crosses over the more northerly and southerly locations of its orbit. Due to this recurrence, latitudinal analysis was made on a yearly basis in order to facilitate sufficient data for valid comparisons to be made.
1.5. Research Objectives

Characterizations of specific twilight airglow from the SABER sensor aboard the NASA TIMED satellite have been conducted. Results are presented for peak volume emission rates (VER) in hydroxyl channels 8 (λ2.06-µm) and 9 (λ1.64-µm) during twilight. The SABER data provide a unique perspective on three-dimensional global characterization of the mesospheric airglow. The SABER data to be used cover the years from 2002 to 2005. The objective of this research is to globally map quantized transition times and rates of the peak VER mesospheric airglow on a yearly basis to facilitate analysis of the morning and evening twilight behavior as a function of latitude in each emission band. Only the rates will be included in this report in graphical form.

2. DATA ANALYSIS

In order to portray twilight VER times and rates of change at twilight, it first becomes necessary to validate the data being used and ensure that true VER measurements are being properly separated from noise components of the data. Techniques implemented as part of this research are given here in part (see [6] for the full details).

2.1. Altitude Profiles

By viewing the altitude profiles of each channel of data, key information can be gained which can lead to simplified methods of separating noise sources of vibrations within the passbands of these filters from the true emission data. One particular contamination source within the passbands is that of scattered sunlight. This phenomenon only occurs during the daytime because it is a result of sunlight bouncing off molecules in the atmosphere, thus masking airglow emissions by contributing to activity for a large range of frequencies. Indications of scattering are apparent in daytime data of both hydroxyl channels of SABER. Figure 4 shows how scattering data might be misinterpreted as hydroxyl VER on an altitude profile for SABER channel 9. True emissions have an average altitude of above 80 km, and values below 70 km can definitely be attributed to scattering in the OH λ1.64-µm channel.

Fig. 4. Channel 9 altitude profile during the daytime on day 100, 2002. This scan shows the need of a limiting threshold to prevent including erroneous peak VER values. Here, at an altitude of approximately 70 km, the data values represent scattered light, exceeding the peak VER magnitude and producing misleading values within the radiometric band.

2.2. Stochastic Models

In order to make conclusions as to which altitudes of data should be included in data analysis of the SABER hydroxyl channels, stochastic models are needed of both the scattering in each channel and the peak hydroxyl VER. Finding the maximum likelihood threshold between the two entities involves determining the probability density function (pdf) of both sources of data, namely the peak VER data and the scattering data that threaten to override correct values.

Both the altitudes of the peak emissions and the altitudes of the scattering values that could lead to erroneous airglow measurements (see fig. 4) were determined to be Gaussian distributed. This assumption produces good estimates for altitude thresholds. Figure 5 illustrates the relationship between the estimated densities of altitudes of peak VER in the OH λ1.64-µm channel and that of the altitude of the first overriding scattering data point. Gaussian random variables can be completely characterized by their mean and variance. The density function for a Gaussian random variable \( x \) with mean \( \mu \) and variance \( \sigma^2 \) is given as

\[
f(x) = \frac{1}{\sqrt{2\pi\sigma}} e^{-\frac{1}{2\sigma^2}(x-\mu)^2}.
\]

Assuming these densities to be closely approximated, the best threshold decision that can be made
which, when simplified, can be expressed as

\[ l(x) = \frac{f(x|\theta_1)}{f(x|\theta_0)}, \quad (4) \]

which can be expanded as

\[ l(x) = \frac{1}{\sqrt{2\pi}\sigma_1} e^{-\frac{1}{2\sigma_1^2}(x-\mu_1)^2} - \frac{1}{\sqrt{2\pi}\sigma_0} e^{-\frac{1}{2\sigma_0^2}(x-\mu_0)^2}, \quad (5) \]

and rewritten in the form

\[ l(x) = \frac{1}{\sigma_1} e^{-\frac{1}{2\sigma_1^2}(x-\mu_1)^2} \left[ 1 - \frac{1}{\sigma_0} e^{-\frac{1}{2\sigma_0^2}(x-\mu_0)^2} \right]. \quad (6) \]

Finally, in taking the natural logarithm of the likelihood function the log-likelihood ratio can be formed, which, when simplified, can be expressed as

\[ \Lambda(x) = \log\left(\frac{\sigma_0}{\sigma_1}\right) - \frac{(x-\mu_1)^2}{2\sigma_1^2} + \frac{(x-\mu_0)^2}{2\sigma_0^2}. \quad (7) \]

The log-likelihood ratio for \( x \in [65, 85] \) is plotted in fig. 6. Note that the original value sought for a maximum likelihood threshold value was that altitude that produced the same probability in both density functions. This value can be chosen by inspection of the likelihood ratio. The altitude that most closely gives the value of unity in this ratio is the desired threshold value. Equivalently, the altitude that most closely approximates zero for the log-likelihood ratio is the desired threshold value. Figure 6 shows this value to be an altitude of 78.12 km in the SABER OH \( \lambda 1.64-\mu \text{m} \) channel. This analysis was repeated, yielding a threshold value of 78.15 km with a different data set, thus increasing confidence in the estimated parameter. The value that was used in the final altitude filtering of each data scan was 78.15 km.

The same analysis was performed with the OH \( \lambda 2.06-\mu \text{m} \) channel. It was found that the scattering did not affect the longer wavelength channel as much as the OH \( \lambda 1.64-\mu \text{m} \) channel. The altitude threshold calculated for the OH \( \lambda 2.06-\mu \text{m} \) channel was 72.81 km.

2.3. Global Binning

A method for comparing twilight transitions relative to geographic location was implemented for mesospheric SABER data analysis at twilight. The comparison between twilight at different latitudes motivates a global binning algorithm. The data are first binned according to latitude and longitude, and then binned temporally relative to sunrise and sunset. In this way, binned time
transitions are created for a localized geographic region. Examples of temporally binned data are seen as the noisy signals in fig. 7 and are referred to as twilight transition curves.

After completing this task, it is easier to compare twilight transitions by deriving a rise or fall time and rate value for each twilight transition. This is also shown in fig. 7, where the binned data are fitted to a polynomial, which is then analyzed at points 10% and 90% through the transition during sunset. Notice that if another increase in emissions occurs a few hours after sunset (as in yaw cycle F), it is ignored by this technique. These examples of yaw cycles A and F in 2005 yield rise times of 0.94 hours and 0.95 hours, respectively. Rise or fall time calculations can be converted to a rate of change parameter by simply dividing the change in emission magnitudes by the time difference between the 10% and 90% points. This is also analogous to calculating the slope of a straight line connecting the 10% and 90% points.

If this analysis is conducted within each geographic bin over the globe, plotting the time or rate values on a color scale over a projection of the globe can portray latitudinal characteristics during twilight. A hybrid Kriging/cubic-spline interpolation technique [7] is used to smooth the discrete results over map projections. This method of interpolation has been found to outperform interpolation methods incorporated in Matlab in the mean squared error sense using test patterns of various types [7]. This hybrid Kriging method is used to plot interpolated data overlaid on Mercator map projections using the Matlab toolbox m_map written by Rich Pawlowicz and Deirdre Byrne.

The geographic resolution must be set to ensure that sufficient data points are included in each of the transitions. This technique necessitates inclusion of an entire year’s worth of data to ensure enough local data are available to construct time transition curves in each geographic bin. Results of the interpolation can be seen when comparing figs. 8 and 9. Figure 8 shows the discrete values for each geographic bin, while fig. 9 gives the Kriging interpolated version.

**Fig. 7.** Two examples of rise time values calculated for the SABER OH λ1.64-µm channel for yaw cycles A and F in year 2005.

**Fig. 8.** Sunset rise times of globally-binned data averaged over 2002 for OH λ2.06-µm SABER data.

### 3. RESULTS AND DISCUSSION

Geographic bins of resolution 10° latitude by 40° longitude were used to implement the global binning algorithm. Latitudinal effects are more inherent than longitudinal effects in the data; therefore, binning was conducted to maintain higher resolution in the latitudinal direction. Approximately thirty data points per time bin per geographic bin were obtained, which provide reliable bin averages in these data sets. Two hundred time bins over 24 hours comprise the twilight transition curves for each geographic bin relative to sunrise and sunset. The twilight transition curves were further interpolated using a lowpass interpolation technique to provide higher resolution in the curves within each geographic bin. Analysis of these plots yields information on the characterization of hydroxyl twilight ten-
Fig. 9. Interpolated version of sunset rise times of globally-binned data averaged over 2002 for OH $\lambda 2.06$-µm SABER data using the hybrid Kriging method.

The OH $\lambda 1.64$-µm globally-binned data exhibit variations of rise times and rates between near-equatorial latitudes and midlatitudes. Evidence of an equatorial effect in the hydroxyl airglow is apparent upon inspection of the rates of increase and decrease calculated at sunset and sunrise as can be seen in figs. 10 and 11, respectively. These equatorial enhancements show faster rise times during sunset at near-equatorial latitudes than at midlatitudes (fig. 10), and slower fall rates at near-equatorial latitudes than those at midlatitudes during sunrise (fig. 11).

Faster rise rates at the equator were the most pronounced in 2002, and then waned every year thereafter through 2005. The equatorial effect of slower fall rates at the equator is almost unnoticeable in 2002, and was enhanced each year, showing the slowest equatorial sunrise transitions in 2005. The faster transitions at the equator are due to the fact that the VER is higher at the equator, but rise times across latitudes are basically constant. The equatorial slower fall rates are due to the finding that peak VER values at midlatitudes are greater than those at the equator directly preceding sunrise. Figure 12 shows this phenomenon in the OH $\lambda 2.06$-µm channel. The same characteristic holds true for OH $\lambda 1.64$-µm, but is not as pronounced in the shorter wavelength channel. The OH $\lambda 2.06$-µm channel shows similar geographic tendencies to those found

Fig. 10. Kriging interpolation of globally-binned twilight transition rates at sunset in SABER channel 9 (OH $\lambda 1.64$-µm).

Fig. 11. Kriging interpolation of globally-binned twilight transition rates at sunrise in SABER channel 9 (OH $\lambda 1.64$-µm).
in the OH λ1.64-µm channel, as can be seen in figs. 13 and 14.

4. CONCLUSIONS

Globally-binned data were presented and mapped using a hybrid Kriging/cubic-spline interpolation technique [7]. These mappings displayed quantized rise and fall times/rates over latitudes in the range of ±60°. Analysis of these plots revealed equatorial characteristics in the rise and fall rates/times of both channels of SABER hydroxyl data. Conclusions on analyses of these data are given as follows:

1. Near-equatorial latitudes exhibited faster rise rates during sunset than midlatitudes by a factor of two for both hydroxyl channels signifying higher VER near the equator after sunset because of the roughly uniform rise times across latitudes.

2. The hydroxyl emission bands show slower fall rates at the equator by an approximate factor of two signifying higher VER at midlatitudes when compared with near-equatorial latitudes directly preceding sunrise. Sunrise also exhibited similar fall times across latitudes.

3. Equatorial effects of faster rise rates at the equator were most pronounced in the year 2002, and decreased each year until 2005.
4. Equatorial effects in both hydroxyl radiometric channels of slower fall rates at the equator were slight in the year 2002, but were more pronounced each year through 2005.

These effects show correlations with the solar cycle, where years 2002 to 2005 exhibited decreasing sunspot counts each succeeding year [8].

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6. REFERENCES


