Submitted to *Advances in Space Research*, March, 1997

ENERGETICS OF THE MESOSPHERE AND LOWER THERMOSPHERE AND THE SABER EXPERIMENT

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ABSTRACT

The energy budget of the mesosphere and lower thermosphere is governed by numerous sources and sinks of energy including radiative, chemical, and dynamical processes. Many of the radiative and chemical processes occur far from local thermodynamic equilibrium. The various radiative and chemical sources and sinks of energy will be briefly reviewed in this paper. In addition, the Sounding of the Atmosphere using Broadband Emission Radiometry (SABER) Experiment, presently under development for the Thermosphere-Ionosphere-Mesosphere Energetics and Dynamics (TIMED) mission, will be introduced. SABER is an infrared emission limb sounder which will observe, at high radiometric accuracy, emissions from carbon dioxide (15 μm), ozone (9.6 μm), and nitric oxide (5.3 μm) to assess temperature, radiative cooling, and ozone abundances. SABER will also observe the singlet-delta molecular oxygen emission (1.27 μm), the Meinel bands of the hydroxyl radical (1.6 and 2.0 μm) , water vapor (6.7 μm), and carbon dioxide emission at 4.3 μm. From these measurements a virtually complete computation of the radiative and chemical heating and radiative cooling rates in the mesosphere and lower thermosphere can be obtained.

INTRODUCTION

The mesosphere and lower thermosphere have long been studied using ground-based observations, rocket flights, and satellite experiments. In particular, the Solar-Mesosphere Explorer (SME) satellite which operated in the mid-1980's and the Upper Atmosphere Research Satellite (UARS) which is operational in the 1990's both carried instruments to investigate aspects of mesospheric composition and structure. In particular, SME measured ozone and temperature while instruments aboard the UARS satellite measure temperature, winds, ozone, and airglow features in the mesosphere. To date, however, there has not been a focused investigation of this region in which solar inputs, winds, temperatures, constituent abundances, and key radiative emissions related to the energetics are measured.

At present, the National Aeronautics and Space Administration (NASA) is developing a new mission called TIMED--Thermosphere-Ionosphere-Mesosphere Energetics and Dynamics--to conduct an in-depth investigation of the mesosphere and lower thermosphere, nominally the region between 60 and 180 km in altitude. Four experiments have been selected to fly on this mission which is scheduled to be launched in January, 2000. One of those instruments, the Sounding of the Atmosphere using Broadband Emission Radiometry (SABER) experiment, is being developed by NASA's Langley Research Center in cooperation with Utah State University and with Hampton University to examine in detail the heat budget of this region.

The thermal structure of the mesosphere and lower thermosphere is determined by a number of mechanisms through which the region gains and loses energy. It is not the intent here to provide an in-depth review of the thermal structure and energetics. Rather the goal is to provide an overview of some critical processes and to

discuss how the SABER experiment will provide fundamental measurements that will enable a significant advance in our understanding of the heat budget.

A main source of energy into the mesosphere and lower thermosphere is solar ultraviolet radiation. The processes by which solar energy is converted to heat, including exothermic reactions and airglow reduction of the solar heating efficiency have been discussed previously /1/. Ozone is a key species in the heat budget, participating in up to 80% of the combined solar and chemical reaction based heating between 50 and 100 km /2/. Thus, it is of paramount importance to have accurate measures of the ozone profile in order to understand the basic process of solar heating below 100 km. Between 80 and 100 km, exothermic chemical reactions have been found to provide heating which exceeds that directly deposited by solar ultraviolet radiation /1,3/. Thus it is also necessary to develop an observation approach which will allow the magnitude of these reactions to be estimated.

Energy is lost from this region of the atmosphere through the emission of infrared radiation. In particular, the 15-μm bands of carbon dioxide are important below ~130 km, while nitric oxide (NO) emission at 5.3 μm is thought to be important from about 110 km up to at least 200 km. Ozone also acts to cool the mesosphere, but only below about 80 km. Water vapor emission, in both the fundamental vibration-rotation band at 6.7 μm and in the rotational bands, is important in atmospheric cooling below about 65 km.

An overarching goal of the SABER experiment is to provide measurements of chemical species such as ozone in addition to measurements of temperature and key emission features such as the Meinel bands of the hydroxyl radical in order to accurately assess the rates of solar heating, chemical heating, and infrared cooling in the mesosphere and lower thermosphere. These measurements, combined with accurate determination of the temperatures (and measurements of winds and solar inputs from other TIMED experiments) will allow the radiative and chemical contributions to the heat budget to be assessed and also the net effect of dynamics to be inferred.

THE SABER EXPERIMENT

SABER is an infrared radiometer which observes emission from the earth's limb in 10 relatively narrow spectral intervals. It has a 2 km instantaneous field-of-view which scans the earth limb from the earth's surface to 400 km tangent altitude. Profiles of emitted radiance are recorded simultaneously through one telescope in all 10 spectral channels. These profiles will then be analyzed using a variety of non-LTE models in order to derive profiles of kinetic temperature, minor species concentration, energy loss rates, solar heating rates, chemical heating rates, and radiative cooling rates. The SABER radiometer will be accurately calibrated to better than 5% (3% is the goal) in all spectral channels. A list of SABER channels and applications is given in the Table below.

SABER will determine the kinetic temperature of the atmosphere using the standard "two-color" technique for infrared sensing described by Gille and House /4/. Emission from carbon dioxide at 15 μm is sensed in two different spectral intervals. From this data, the temperature and pressure can be determined simultaneously. A key to the interpretation of the SABER 15 μm emission measurements in terms of kinetic temperature will be knowledge of the departure from local thermodynamic equilibrium in the upper mesosphere and lower thermosphere. The relatively recent work of Sharma and Wintersteiner /5/ and of Rodgers et al. /6/ suggest that LTE in the fundamental and first hot bands of carbon dioxide exists to much higher altitudes (perhaps 90-95 km) than previously thought. Thus, relatively small corrections should be in order to account for the departure from LTE in the bands observed by SABER. A complete error analysis is now underway to assess the accuracy to which kinetic temperatures can be retrieved from the measurements of non-LTE emission by SABER.

The SABER instrument will be sensitive to 15 μm emission up to an altitude of about 135 km. Despite the likely occurrence of non-LTE in the fundamental band between 100 and 135 km, the SABER radiance data

Table 1. SABER Channels and Science Applications

Parameter	λ (μm)	Science Application	Altitude Range
CO_2	15	Kinetic temperature; altitude and pressure registration; infrared cooling rates; non-LTE/LTE nature of CO_2	10-135
O_3	9.6	Ozone concentration; cooling rates; solar heating rates; fundamental chemistry and dynamics studies	15-100
$O_2(^1\Delta)$	1.27	O_3 concentration (daytime); energy loss; Inferred atomic oxygen at night	50-105
CO_2	4.3	CO_2 concentration 85 - 140 km; upper mesosphere solar heating; dynamical tracer above 90 km	85-140
OH(υ)	2.0 1.6	Emission used to infer [H], [O]; Chemiluminescent energy loss; dynamics/wave studies; polar mesospheric cloud studies; chemical heating derivation	80-100
NO	5.3	Thermospheric cooling; NO_X chemistry	90-180
H_2O	6.9	Odd-hydrogen source gas; dynamical tracer; lower mesospheric cooling	15-80

can be used to directly assess the energy loss by CO_2 emission at these altitudes. A relatively straightforward Abel-type inversion can be used to directly obtain the energy loss rate (energy per unit volume per unit time). To the extent that the non-collisional excitation processes can be modeled, this measurement can provide accurate cooling rates (in K/day) due to CO_2 emission. The non-LTE models of Lopez-Puertas et al. /7/ will be used in the analysis of the CO_2 emission data.

Daytime ozone will be determined by SABER through two different techniques. Emission by the fundamental asymmetric stretch bands of ozone in the vicinity of 9.6 μm will be observed in order to derive the ozone concentration using emission directly from the ozone molecule itself. The data will be analyzed using the non-LTE models as described in Mlynczak and Drayson /8, 9/. The SABER spectral bandpass for this channel is 1010-1140 cm^{-1} and has been chosen to minimize the contribution from the hot bands of ozone and also from the laser bands of carbon dioxide which provided considerable signal to the Limb Infrared Monitor of the Stratosphere (LIMS) experiment /10/. Daytime ozone will also be inferred from measurements of the emission from the molecular oxygen dayglow $O_2(^1\Delta)$ at 1.27 μm. This technique was applied in the SME experiment and will provide a second measure of daytime ozone on the SABER experiment. In addition, the energy emitted by $O_2(^1\Delta)$ significantly reduces the solar energy available for heat. The direct determination of the $O_2(^1\Delta)$ volume emission rate along with simultaneous measures of the temperature and pressure allows the solar heating efficiency to be determined directly from the SABER measurements. This can be accomplished as discussed in Mlynczak and Solomon /1, 11/. An error analysis of the 1.27 μm measurement has been performed /12/.

The ozone concentration at night will be provided by measurements at 9.6 μm. The SABER instrument will have sufficient sensitivity to record ozone emission to 100 km altitude (day and night). The choice of the spectral interval and the specifics of the non-LTE problem /8, 9/ make the retrieval of nighttime ozone under non-LTE conditions relatively straightforward. An error analysis of the kinetic and spectroscopic parameters which compose the non-LTE model for ozone is now underway, with requirements for parameter accuracy to be published shortly.

The SABER instrument will observe the strong CO_2 emission at 4.3 μm. This band has been observed on the Stratospheric and Mesospheric Sounder (SAMS) experiment which flew in the 1970's on Nimbus 7 and also on the Improved Stratospheric and Mesospheric Sounder (ISAMS) which flew on the Upper Atmosphere Research Satellite. The main purpose for this measurement on SABER is to provide a measure of a long-lived tracer (i.e., CO_2) in the lower thermosphere, approximately 100-140 km. The models of Lopez-Puertas et al. /13/ will be used in the analysis.

One of the keys to understanding the heat budget between 80 and 100 km will be to understand the chemical heating processes. One of the most significant reactions in this region is that which occurs between atomic hydrogen and ozone. This reaction results in the creation of vibrationally excited hydroxyl and hence the Meinel bands. SABER will observe emission from the Meinel bands in two different spectral regions. The first channel, centered near 2.0 μm, will observe emission from vibrationally excited states of hydroxyl lying near the dissociation limit, specifically υ = 7, 8, and 9. These states are formed directly upon the reaction of atomic hydrogen and ozone. Hence, a measure of the radiative emission from these states (coupled with SABER ozone and temperature measurements) can be used to directly derive the rate of heating by this highly exothermic reaction. A second hydroxl emission channel is located at 1.6 μm and will sense emissions from the mid-υ vibrational levels, primarily υ = 4, 5, and 6. This channel is included for two reasons. First, to study the energy flow through the hydroxyl molecule from high to low υ and second, to assess the possibility of production of vibrationally excited OH from the reaction of atomic oxygen with the hydroperoxyl (HO_2) radical which is capable of populating OH up to υ = 6. Finally, the combination of the two hydroxyl channels can be used to examine large scale dynamics through global maps of the airglow intensity.

One of the most exciting measurements to be made by SABER is the measurement of infrared emission from nitric oxide (NO) at 5.3 μm. This feature is thought to be the single largest radiative cooling mechanism in the lower thermosphere. The cooling is accomplished by excitation of NO through collisions with atomic oxygen which may be followed by radiative emission, and hence cooling (loss of kinetic energy) of the atmosphere. A straightforward Abel inversion will yield directly the NO volume emission rate as a function of altitude, accurate to a few percent. When multiplied by the photon energy, the volume emission rate becomes a direct measure of the energy loss rate of the thermosphere through NO emission. Further non-LTE modeling of the excitation and quenching processes will be required to establish what fraction of the observed volume emission rate that is actually associated with loss of kinetic (translational) energy from the lower thermosphere.

Last but not least is a channel designed to sense emission by water vapor at 6.9 μm. Water vapor molecules are the source of odd-hydrogen in the mesosphere. It is the odd-hydrogen which then proceeds to interact with the odd-oxygen family and produces the chemical loss of ozone in the lower mesosphere. The simultaneous measurement of ozone (two techniques), water vapor, and temperature will enable a more complete understanding of the mesospheric ozone chemistry.

Finally, the SABER measurements have been chosen to allow an inference of atomic species. In particular, the measurements can be used to infer atomic hydrogen and atomic oxygen, the latter in at least 3 different ways which together cover the altitude range from 50 to 135 km. Atomic hydrogen can be inferred from the combination of SABER 2.0 μm measurements of hydroxyl emission. The high-υ states are produced directly upon reaction of H and O_3. SABER will independently measure the ozone abundance. Thus, the measured

high-υ OH emission rate which is proportional to the product of H and O_3 can be used in conjunction with the SABER O_3 measurement to derive directly the concentration of atomic hydrogen.

Atomic oxygen can be derived from SABER measurements in a number of ways. Between 50 and 80 km, an estimate of the daytime atomic oxygen concentration can be obtained by looking at the diurnal variation of ozone at these altitudes. At night, all of the atomic oxygen is converted to ozone, causing an increase in the ozone abundance. The day/night differences in ozone are then an indicator of the total amount of atomic oxygen. In addition, the $O_2(^1\Delta)$ measurement provides a measurement of the atomic concentration at night between 80 and 100 km. The recombination of atomic oxygen at night results in the generation of O_2 emission at 1.27 μm. Clearly, significant kinetic modeling is required to derive the atomic oxygen concentration, but it has been done before with SME data /14/. A third approach to deriving atomic oxygen concentrations from SABER measurements would involve the use of SABER 15 μm emission measurements between 100 and 135 km. A primary excitation source is thought to be through collisions with atomic oxygen. Thus the volume emission rate (which again can be determined through an Abel inversion) coupled with knowledge of the CO_2 concentration from the 4.3 μm measurements gives an estimate of the rate of excitation by collisions with atomic oxygen. Hence, to the extent that the collisional excitation rate constant known, it is possible to derive atomic oxygen concentrations from this combination of SABER measurements. Clearly, however, this will be a highly derived product with correspondingly large uncertainties.

SABER DATA PRODUCTS

SABER will provide numerous data products for the scientific community at large to use in studies of the composition and structure of the mesosphere and lower thermosphere. These are divided into two classes, “Routine” and “Analysis”. Routine products are those which will be produced ‘routinely’ in regular processing of the SABER data. SABER Analysis Products are defined as those which require additional post-processing of the of the Routine Products. The post processing may involve use of a photochemical model, the TIME-GCM, data from other TIMED instruments, data from several SABER channels, or combinations of these. It is expected that generation of the SABER Analysis Products will be highly interdisciplinary in nature. The combined set of SABER data products will give a nearly complete measure of solar heating, chemical heating, and infrared radiative cooling in addition to temperature and ozone, and water vapor concentrations.

SABER Routine Products are:

- Kinetic Temperature, pressure, and density (10-105 km), day and night
- Ozone concentrations (15-100 km, from 9.6 μm), day and night
- Ozone concentrations (50-105 km, from 1.27 μm), daytime only
- Water vapor (15-80 km), day and night
- Nitric Oxide volume emission rate at 5.3 μm (100-180 km), day and night
- Hydroxyl volume emission rate at 1.6 μm (80-100 km), day and night
- Hydroxyl volume emission rate at 2.0 μm (80-100 km), day and night
- $O_2(^1\Delta)$ volume emission rate at 1.27 μm (50-100 km), day and night
- CO_2 (4.3 μm) calibrated limb radiance profile
- CO_2 (15 μm) calibrated limb radiance profile
- Calibrated limb radiance profiles for all remaining channels

SABER Analysis Products are:

- Constituent Abundances: CO_2 (100-160 km); O (80-100 km); H (80-100 km)
- Cooling Rates: CO_2(15 μm); NO (5.3 μm); O_3 (9.6 μm); H_2O (6.7 μm and far-infrared)
- Chemical Heating Rates (Odd-Oxygen and Odd-Hydrogen families)
- Solar Heating Rates (including airglow losses):
  - O_3 (Hartley, Huggins, Chappuis, and other UV) and CO_2(near-ir)
  - O_2 (Schumann-Runge, Ly-α, Herzberg, and Atmospheric Bands)

SUMMARY

The mesospheric energy budget remains a frontier of atmospheric science research. While there has been great progress in the last several years regarding the relative importance of specific processes, there is still a lack of consistent measurements with which to fully quantify the heat budget. An exciting new mission, the TIMED mission, is now under development for launch early in the year 2000 for the first comprehensive examination of this region. The SABER experiment on the TIMED mission will provide numerous key measurements which will serve to quantify the heat budget, the chemistry, and the dynamics of the region.

ACKNOWLEDGMENT

I would like to thank my many colleagues for their insights and for numerous discussions over the years. I would also like to thank Dr. Juergen Roettger and the Organizing Committee for the invitation to speak at COSPAR 1996.

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