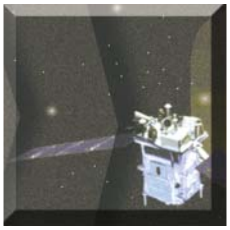

TIMED Mission Science Overview

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The Thermosphere, Ionosphere, Mesosphere Energetics and Dynamics (TIMED) mission is a low-cost NASA Sun-Earth Connections mission designed to provide a basic understanding of the least explored and least understood region of the Earth's environment—the mesosphere, lower thermosphere, and ionosphere (MLTI). The MLTI region is located approximately 60 to 180 km above the surface and is a gateway between the Earth's lower atmosphere, in which we live, and space. The TIMED suite of four remote sensing instruments measures energy inputs and outputs in the MLTI region as well as its basic structure, including seasonal and latitudinal variations. Over its 2-year mission, TIMED is investigating the relative importance of various radiative, chemical, electrodynamic, and dynamic processes that govern the structure and variability of the MLTI region. This article presents an overview of TIMED mission science and objectives.

BACKGROUND

Although our knowledge of the near-Earth space environment has increased enormously since the start of the Space Age, many significant gaps still exist, and our ability to model the variability of the system as a whole remains rudimentary at best. The Sun, its atmosphere and heliosphere, and the Earth's magnetosphere and atmosphere are coupled by important physical processes that are only partially known (NASA Strategic Plan, 1994, http://umbra.nascom.nasa.gov/solar_connections.html). NASA's Sun-Earth Connections program (http://sec.gsfc.nasa.gov/) is an integrated and balanced flight program designed to observe and interpret the variable solar and georadiation spectra observed in the near-Earth space environment and to gain insight into the impact of solar activity on our terrestrial environment.

The TIMED mission is the first of the Solar Terrestrial Probes under the Sun-Earth Connections program designed to quantitatively understand the energetics and dynamics of Earth's mesosphere, lower thermosphere, and ionosphere (MLTI), a region of the atmosphere about 60 and 180 km above the surface. (Complete information on the TIMED mission, including participants, status, science, etc., may be found at http://www.timed.jhuapl.edu/mission/.) The MLTI is a transition region between the Sun and the lower atmosphere in which we live. It shields us from the Sun's harmful ultraviolet (UV), extreme ultraviolet (EUV), and X-ray radiation. It also hosts majestic auroral displays at high latitudes and has the coldest temperature and highest clouds (noctilucent clouds) found in the Earth's atmosphere.

Because it is a transition region, the MLTI is affected by the Sun's highly variable energy inputs. It exhibits short-term (daily) weather-like and mid-term (seasonal) climate-like variabilities as well as strong long-term (11-year) solar cycle variability. In addition, to the best of our theoretical knowledge, the MLTI may also exhibit long-term modifications due to human-induced changes in the lower atmosphere. Yet to date, scientists have no comprehensive measurement base to determine the basic structure of the MLTI or understand the processes that control its variabilities. Our current understanding of the region is derived mainly from observations obtained from ground-based instruments and rocket flights that have very limited spatial and temporal coverage (Fig. 1). Recent satellites (Atmospheric Explorer, Dynamics Explorer, Solar Mesosphere Explorer, Upper Atmosphere Research Satellite) have provided some observational data to address specific scientific issues related to parts of the MLTI region, but have also raised more questions regarding the basic structure of the MLTI region as a whole and how it couples internally and externally with the Sun and the lower atmosphere.

TIMED is designed to collect at least 2 years of continuous global observations of atmospheric state parameters (i.e., pressure, temperature, and winds) and the simultaneous energy inputs and outputs to improve our theoretical understanding of this least explored region of Earth's atmosphere.

This article discusses the science objectives of the TIMED mission, and the instruments needed to meet those goals are briefly described. An in-depth examination of the MLTI region follows. Finally, anticipated science returns from the mission are summarized.

TIMED SCIENCE OBJECTIVES

The primary objectives of the TIMED mission are to investigate and understand the basic structure, spatial and temporal variation, and energy balance of the MLTI region. A suite of onboard instruments has been collecting an unprecedented set of mid- and upper-atmospheric measurements to address two specific goals:

1. To determine the temperature, density, and wind structure in the MLTI region (60–180 km), including seasonal and latitudinal variations
2. To determine the relative importance of the various radiative, chemical, electrodynamic, and dynamic energy sources and sinks that govern the thermal structure of the MLTI region

TIMED's four remote sensing instruments (Fig. 2), briefly described here, are providing the critical measurements needed to characterize the energy inputs, energy outputs, and basic states of the MLTI region. Detailed descriptions of the instruments, their measurement capabilities, and sample measurements can be found in articles by Kusnierkiewicz ("An Overview of the TIMED Spacecraft") and Yee et al. ("TIMED Instruments"), elsewhere in this issue.

The Solar Extreme ultraviolet Experiment (SEE) instrument consists of a spectrometer and a suite of photometers that yield measurements of the incoming solar irradiance. The Sounding of the Atmosphere using Broadband Emission Radiometry (SABER) instrument

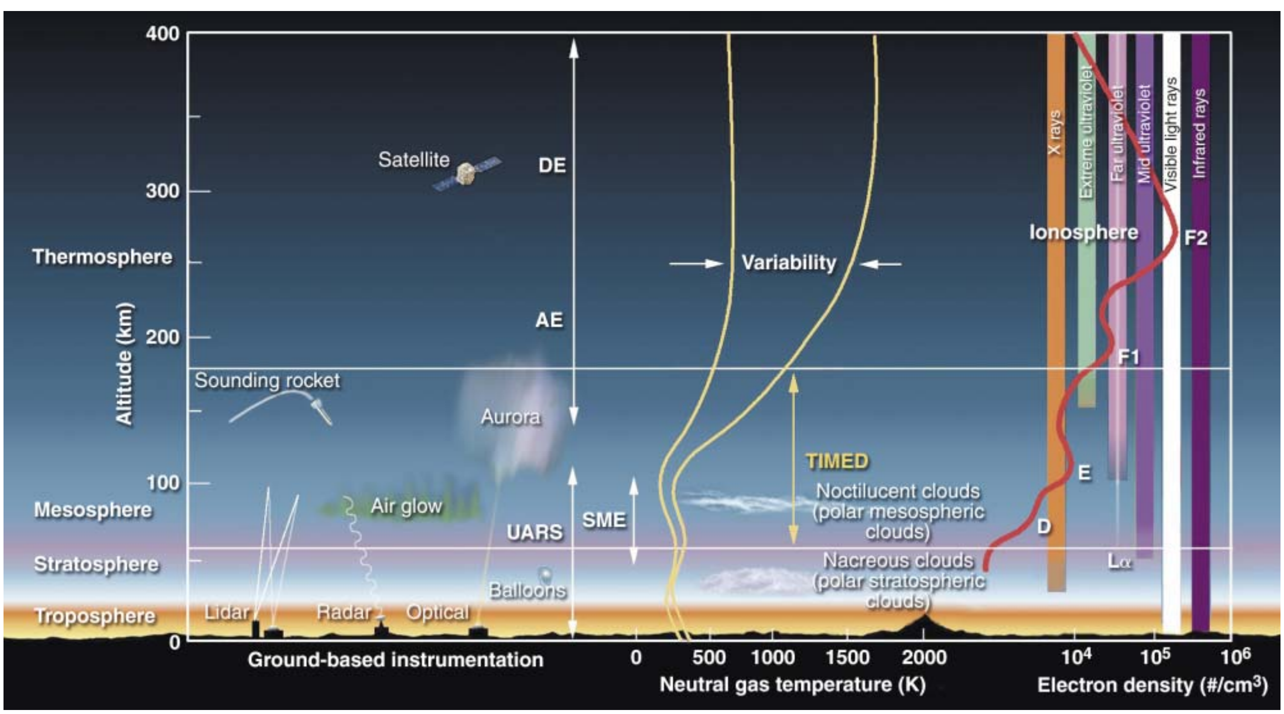

Figure 1. Schematic of the atmospheric thermal structure. The primary altitude regimes of scientific investigations for TIMED as well as those for other past and existing experiments are also indicated (AE = Atmospheric Explorer, DE = Dynamics Explorer, SME = Solar Mesosphere Explorer, UARS = Upper Atmosphere Research Satellite).

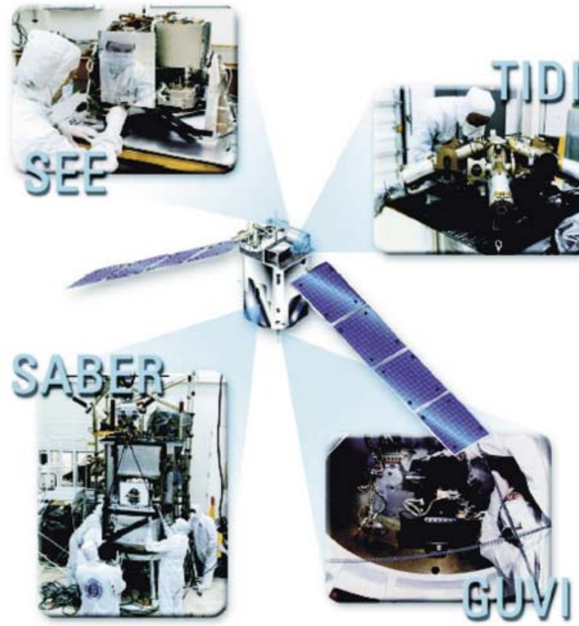

Figure 2. Artist's rendition of the TIMED spacecraft instruments.

is a 10-channel infrared radiometer that measures the pressure, temperature, and infrared cooling rates in the stratosphere, mesosphere, and lower thermosphere. The Global Ultra-Violet Imager (GUVI) is a spatial scanning far-ultraviolet (FUV) spectrograph that measures the thermospheric composition and temperature as well as the auroral particle energy input. The TIMED Doppler Interferometer (TIDI) is a single-etalon Fabry-Perot interferometer that measures horizontal vector winds, temperature, and composition in the mesosphere and lower thermosphere. The TIMED mission also collaborates with numerous ground-based investigators on measurement validation and complementary scientific studies.

TIMED was launched successfully into a 74.1° inclination, 625-km circular orbit on 7 December 2001. The limb-viewing geometry of the onboard instruments is enabling them to provide complete geographic and seasonal coverage of the MLTI. The orbit precesses at a rate of ≈3° longitude (or about 12 min) per day, thus allowing repetitive observations at a specific local time every ≈60 days.

THE MESOSPHERE, LOWER THERMOSPHERE, AND IONOSPHERE

Structure

The thermal structure of the MLTI region varies significantly, both spatially and temporally, around the globe. In a globally averaged sense, it exhibits a local temperature maximum near 50 km (stratopause) and a minimum near 90 km (mesopause), and increasing temperature with height in the thermosphere (Fig. 1). These features directly reflect how the MLTI region responds to solar energy inputs. The temperature maximum results from the absorption of solar UV radiation by ozone (O_3), and the temperature minimum results from the radiative cooling of carbon dioxide (CO_2) at 15.4 μm. Increasing temperature in the thermosphere is due to heat conduction and the absorption of solar EUV and X-ray radiation by atomic oxygen (O), molecular oxygen (O_2), and molecular nitrogen (N_2).

The composition of the MLTI region also exhibits considerable changes from lower to higher altitudes. Because of increasing solar photodissociation, the neutral atmosphere changes from predominantly well-mixed molecular species (O_2, N_2) in the lower atmosphere to mostly atomic species (O, H) separated by gravity in the thermosphere. There is also increasing ionization by solar EUV and X-ray radiation at higher altitudes, resulting in the formation of the ionospheric D, E, F1, and F2 layers illustrated in Fig. 1.

Spatial and temporal variations in the ionosphere significantly impact satellite and radio communications systems, including the Global Positioning System.

Processes

The processes controlling the spatial and temporal variabilities of the MLTI region's composition and thermal structure are in fact more complex than the simple descriptions above. Figure 3 illustrates the energy flow into and out of the MLTI and the physical processes that govern its basic structure and variabilities. Electromagnetic radiation and charged particles from the Sun provide the dominant energy to keep the region's chemical and dynamic engines running. Additional sources of energy include the precipitation of charged particles in the auroral zones, deposition of wave energy propagating upward from the lower atmosphere, and collisional coupling between the neutral and ionized gases in the lower thermosphere. The last source arises because ions in the high-latitude ionosphere are driven to high velocities by magnetospheric electric fields that map into the ionosphere. The resulting collisions convert the electrodynamic energy into heating of the neutral atmosphere. To balance these energy inputs, the MLTI reaches a quasi-equilibrium thermal state by emitting some of the energy out to space through atomic and molecular radiation.

The MLTI undergoes differential heating due to diurnal and seasonal changes in the solar energy input. These changes induce the circulation patterns that affect the global distribution of chemical species. Some of these species are radiatively important themselves; e.g., O_2 and O_3 are the main absorbers of solar UV radiation, and CO_2 and nitric oxide (NO) are the main radiative cooling agents. Other species are involved in chemical reactions that produce or destroy radiatively

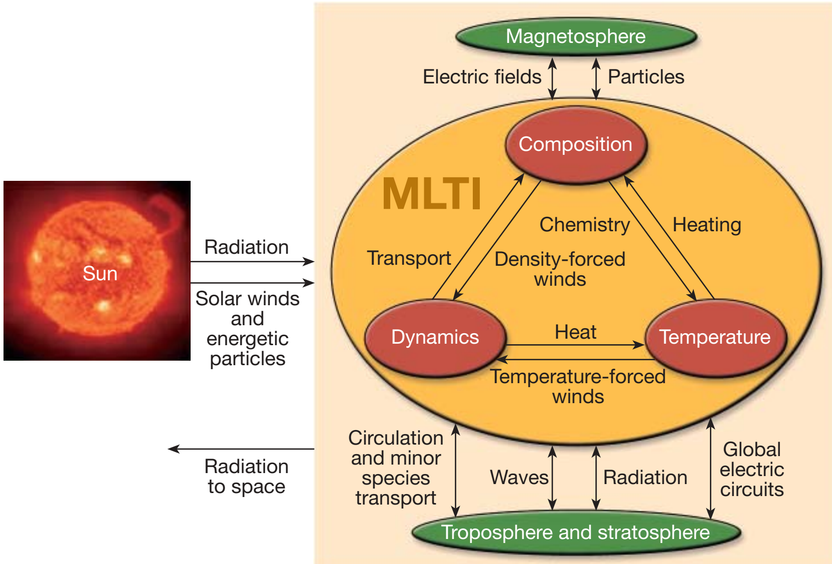

Figure 3. Coupling of the operating region of TIMED—the mesosphere, lower thermosphere, and ionosphere (MLTI)—with the Sun and lower atmosphere.

important species such as O and H, the principal species involved in O_3 chemistry. The dynamically induced chemical transport thus introduces changes in the radiative and thermal balances in the MLTI region that provide further feedback into the dynamic processes. In addition, some chemical reaction rates are temperature dependent, causing the thermal state of the atmosphere to affect the compositional distribution as well.

It is this complex interplay of many physical, chemical, dynamic, electrodynamic, and radiative processes that governs the basic dynamic and thermal states of the MLTI region as well as the response and relaxation timescales of those processes to varying energy inputs. Because of the lack of global well-coordinated measurements, these processes have been identified but not fully investigated. *TIMED is designed to obtain the global observational database necessary to characterize the basic structure of this highly complex region, determine how it varies spatially and temporally, and understand how the energy inputs from the Sun and the lower atmosphere are absorbed, stored, and redistributed.*

Energy Balance

The specific processes addressed by TIMED that are relevant to the MLTI energy balance are illustrated in Fig. 4. They can generally be grouped into three categories: energy sources, energy sinks, and energy transport and redistribution.

Energy Sources

The MLTI region has three main sources of energy: photon radiation from the Sun, particles from the solar wind and magnetosphere, and global electric fields established by Earth's ionosphere and its interaction with the magnetosphere (Joule heating).

Solar irradiance: Solar irradiative energy is deposited into the MLTI region through absorption of X-ray (0.1–20 nm); EUV (20–130 nm) by O, O_2, N_2, and NO; FUV (130–200 nm) by O_2; and mid ultraviolet (MUV, 200–300 nm) by O_3. The energy deposition rate is a function of altitude, latitude, season, and solar activity. Solar MUV irradiance varies very little with solar activity and has been measured by the Upper Atmosphere Research Satellite (http://umpgal.gsfc.nasa.gov). Before TIMED, there were no continuous, accurate solar X-ray and EUV irradiance measurements with which to conduct MLTI energy balance studies. *TIMED is continuously measuring the solar irradiance from 0.1 to 200 nm, the most variable segment of the solar spectrum, along with the simultaneous MLTI response.*

Solar wind and magnetospheric particles: Particles from the solar wind and the Earth's magnetosphere are another significant energy source at high latitudes in the MLTI region. Energy deposited through these particles is highly variable, depending on solar and geomagnetic activity. Subsequent collisions of precipitating particles with the ambient neutral atmosphere not only produce auroral displays but also affect the deposition of solar irradiance: dissociation, ionization, excitation, heating, etc. *TIMED is measuring the auroral intensity seen at UV wavelengths to determine the characteristic energies and fluxes of incoming solar and magnetospheric particles.*

Joule heating: Joule heating is the process by which magnetospheric convection electric fields transfer energy to the neutral atmosphere, thereby coupling the neutral atmosphere, ionosphere, and magnetosphere. In general, ions can be accelerated by the electric fields, and subsequent ion-neutral, neutral-neutral collisions heat the ambient atmosphere. *TIMED, combined with its suite of ground-based instruments, is selectively monitoring the magnitude and variability of this phenomenon.*

Energy Sinks

Collisions of radiatively active chemical species with atoms and molecules in the ambient atmosphere cause internal rotational, vibrational, and fine-structure excitation, followed by radiation to space. This collisionally induced radiation effectively removes kinetic energy, thereby cooling the ambient atmosphere. The most important cooling agent below 120 km is CO_2 at 15.4-μm radiation following the collisional excitation of CO_2 with O. NO emission at 5.3 μm, resulting from NO + O collision, is an important energy sink in the

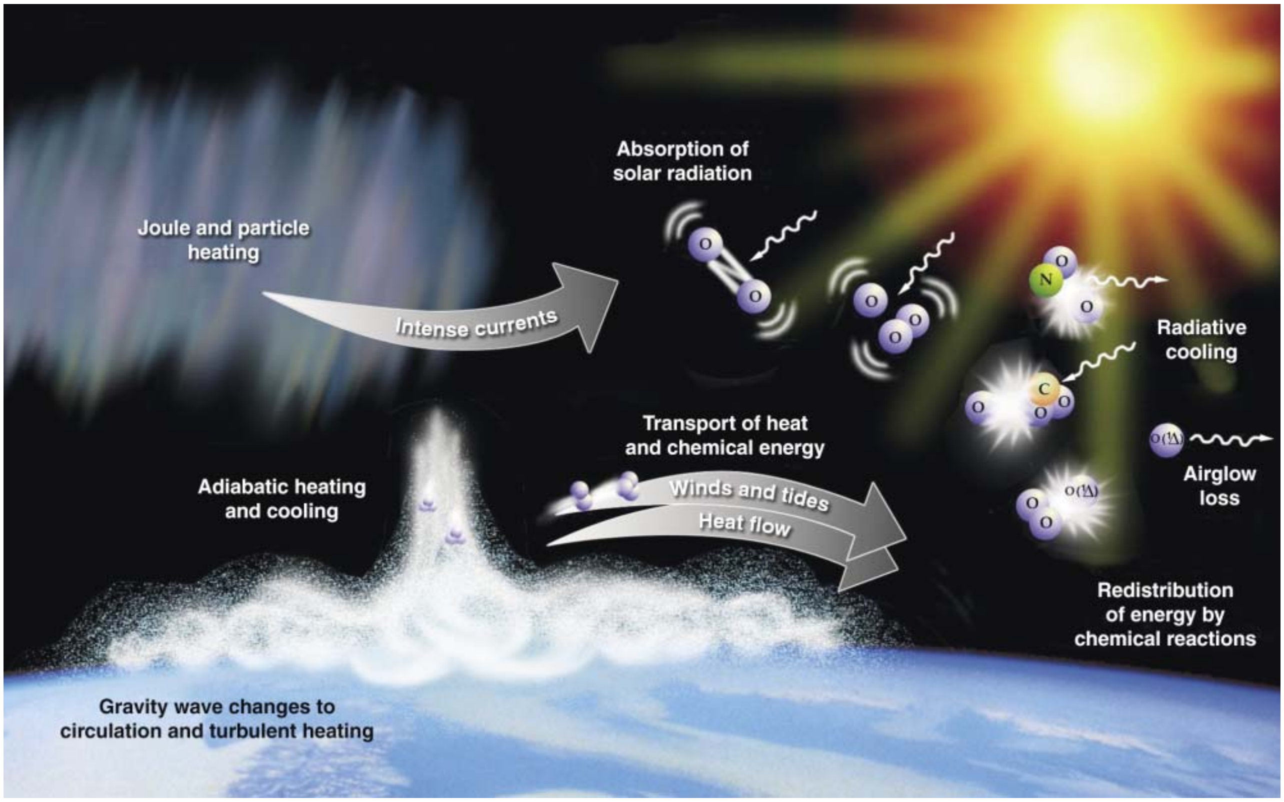

Figure 4. The energy balance in the MLTI is a combination of many important processes that change dramatically. It is a region where energetic solar radiation is absorbed, energy input from the aurora maximizes, intense electrical currents flow, and upwardly propagating waves and tides break.

lower thermosphere (above 110 km), especially at high latitudes, following enhanced auroral production of NO. The other globally important energy sink in the lower thermosphere is fine-structure O at 63-μm radiation following an O + O collision, which can now be successfully calculated if the O density is known. *TIMED is measuring the 15.4- and 5.3-μm radiations globally and infers the 63-μm radiation from its measured O density.*

Energy Transport and Redistribution

Transport of chemical species: In general, solar energy is deposited locally in the atmosphere immediately after excitation, photodissociation, and ionization through subsequent exothermic chemical reactions. However, if the photoreactive products are long-lived or have few collisions (higher altitude), the ambient diffusion and circulation can transport these products to different locations in altitude, latitude, or longitude, and effectively redistribute the initial solar energy. For example, the subsequent chemical reactions involving atomic oxygen, produced from the photodissociation of O_2 in the lower thermosphere, are an effective heat source for the nighttime mesosphere and lower thermosphere. *TIMED is measuring several key chemical species and airglow emissions (such as those associated with atomic oxygen), as well as temperature and winds, to characterize the transport and redistribution of energy around the MLTI region.*

Wave breaking and dissipation: Another mechanism for transport of energy is through wave propagation from the lower atmosphere. Like the ocean, the atmosphere consists of waves of different spatial wavelengths and frequencies. Atmospheric gravity waves are caused by lower atmospheric weather systems and surface topography. These waves propagate upward and grow in amplitude as the density of the air decreases with altitude. Many of these waves become unstable and break much like ocean waves reaching a shore. The breaking of these waves transfers energy and momentum to the background atmosphere and modifies the general circulation pattern of the atmosphere established by differential solar heating. In addition, other large-scale waves such as solar thermal tides (generated from the thermal heating of water vapor and ozone in the lower atmosphere) dissipate their energy in the lower thermosphere. *TIMED is measuring temperature and winds to provide a statistical estimate of wave activity and effects as a function of location and season.*

MLTI Science: Societal Relevance

As noted above, the structure of the MLTI can vary significantly because of the highly variable energy inputs from the Sun and wave activity from the lower atmosphere. Human-induced changes in the lower atmosphere may also affect Earth's upper atmosphere through the increasing concentrations of radiatively important species such as the greenhouse gases (carbon dioxide, methane, water vapor) that are slowly transported to the MLTI region. Unlike the warming greenhouse effect that is predicted in the lower atmosphere, these species provide a net cooling effect in the upper atmosphere (e.g., recall that CO_2 at 15.4-μm radiation is the main cooling agent in the mesosphere). Some scientists believe that the MLTI region can exhibit changes earlier than the lower atmosphere, thus acting as an early indicator of human-induced effects.

One example of such human-induced changes in the MLTI structure may be the increasing occurrence of noctilucent clouds observed during the summer (Fig. 5). Noctilucent clouds are thin and luminous. They are located at extremely high altitudes (roughly 80 km above the surface), much higher than most clouds (about 15 km), and are visible only against a twilight sky. They usually form at latitudes closer to the poles (50° to 60° in both hemispheres), but are now beginning to appear more often and closer to the equator (as low as 40° latitude). Scientists believe this implies that the upper atmospheric regions, which TIMED is studying, are getting colder or richer in water vapor content.

Figure 5. Noctilucent clouds are found in the MLTI region at higher altitudes (about 82 km) than most clouds (15 km). (Photo courtesy of Oscar van der Velde.)

EXPECTED TIMED SCIENCE RETURNS

TIMED achieved its minimum mission success in the spring of 2002. Although TIMED was designed for a minimum mission of 2 years, NASA has extended the mission for additional years of operation and data analysis. Therefore, TIMED will continue to significantly contribute to MLTI science. At the conclusion of its 2-year prime mission, TIMED is expected to enable us to

- Establish the distribution and variability of the region's basic structure (i.e., pressure, density, temperature, and winds)
- Examine the major energy sources (solar radiation and auroral power inputs), transport processes (air motions and heat conduction), and energy sinks (radiative cooling agents) in the region, and apply this information to define the channels by which the energy enters in, transmits through, and is radiated out of the region
- Understand the upper atmospheric circulation pattern, important in the transport of chemically and radiative active species
- Understand the influences of the Sun and outer space on the Earth's middle/upper atmosphere and increase our ability to predict space weather (e.g., satellite drag)
- Establish a benchmark for the current state of the sensitive MLTI region for future studies of natural and human-induced changes to the Earth's atmosphere

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