Chapter 3

Report from Upper Atmospheric Science

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3.1 Introduction

The neutral thermosphere and the ionosphere are physically inseparable, although they are treated separately for the purpose of this report. Advancing scientific understanding of these regions demands an increased understanding of the relationships between the two as well as the couplings from the regions below and above. For the purposes of this report, the upper atmosphere is taken to embrace the region from the base of the mesosphere to the exobase, nominally 50 to 500 km altitude. During the 1970s, our understanding of the mid- and low-latitude thermospheric photochemistry was expanded greatly, largely through the measurements of the Atmosphere Explorers. Thermospheric dynamics have been studied subsequently from the Dynamics Explorer 2 satellite and from ground-based optical and radar observations. The information obtained from these experimental programs has been amplified through the use of large scale models, both physical and empirical. The combined approach enabled the most effective use of observations in deriving information on global dynamic atmospheric processes. Despite considerable progress in understanding the thermosphere, significant gaps remain in knowledge of its behavior. The lower thermosphere, because of a paucity of measurements, is still in need of exploratory study.

Progress in understanding the mesosphere has been much slower largely because of the relative difficulty of direct access and the difficulty thus far in remotely observing the region on a global basis. Our overall knowledge of the region has been pieced together from diverse and isolated measurements. The Upper Atmosphere Research Satellite (UARS) (scheduled for launch in 1991) will concentrate on stratospheric and lower mesospheric measurements. The upper mesosphere, like the lower thermosphere, is still basically unexplored. There is, however, considerable scientific interest in these regions because of nonlocal thermodynamic radiational processes, complex photochemistry, and gravity wave/mean flow interactions that dominates this region. The extent of the downward penetration of solar and auroral variability, that so dominate the thermosphere, into the mesosphere also needs to be determined.

3.2 Background

The thermosphere absorbs extreme ultraviolet (EUV) and UV radiation (wavelength, $\lambda<200$ nm) and, because of the absence of effective IR cooling mechanisms, is heated, giving rise to its name. EUV radiation and precipitating particles ionize the thermosphere and form the ionosphere. Energy and momentum are coupled into the upper atmosphere from the magnetosphere and waves and other disturbances propagating from below deposit their energy as they dissipate over wide ranges of altitudes. The ionospheric plasma is controlled through complex chemical and electrodynamic processes that operate throughout the region with rates dependent on plasma temperature and composition. Finally, the thermosphere becomes the energy sink for plasma. Neutral winds are driven by pressure gradients and ionospheric winds by electric fields of magnetospheric and dynamo origins, and these wind systems interact as they flow within each other. Joule dissipation from the differential motions of plasma and neutral gas is frequently the dominant heat source in some regions. Thermospheric winds redistribute the plasma directly through collisions and indirectly through dynamoelectric fields. In the mesosphere, exotic chemical processes operating in a complex dynamical field produce a highly variable state that begs for elucidation. Most of the operative processes appear to have been identified, but the sensitivity of the resultant state to the details of the interactions causes the models to yield descriptions that are far from reality. The upper atmospheric discipline stands in great need of additional observations, most of them well defined and within measurement capability, to enable the next increment in understanding. The complex suite of processes that operate in the thermosphere-mesosphere system is illustrated in Figure 3-1.

3.3 Outstanding Scientific Problems

The important advances in understanding of the upper atmosphere in the 1970s and 1980s, including recent results from modeling, have also identified a number of outstanding scientific problems. This report identifies four important problem areas. The scientific issues embedded in these areas are related and could have been posed as a greater number of problems, but the four-problem taxonomy seems to cover the main areas.

3.3.1 Mesosphere/Lower Thermosphere Interaction

Because this region is virtually unexplored on a global basis, fundamental questions exist about basic parameters and their variability as well as questions of important chemical, radiative, and dynamical phenomena. These include:

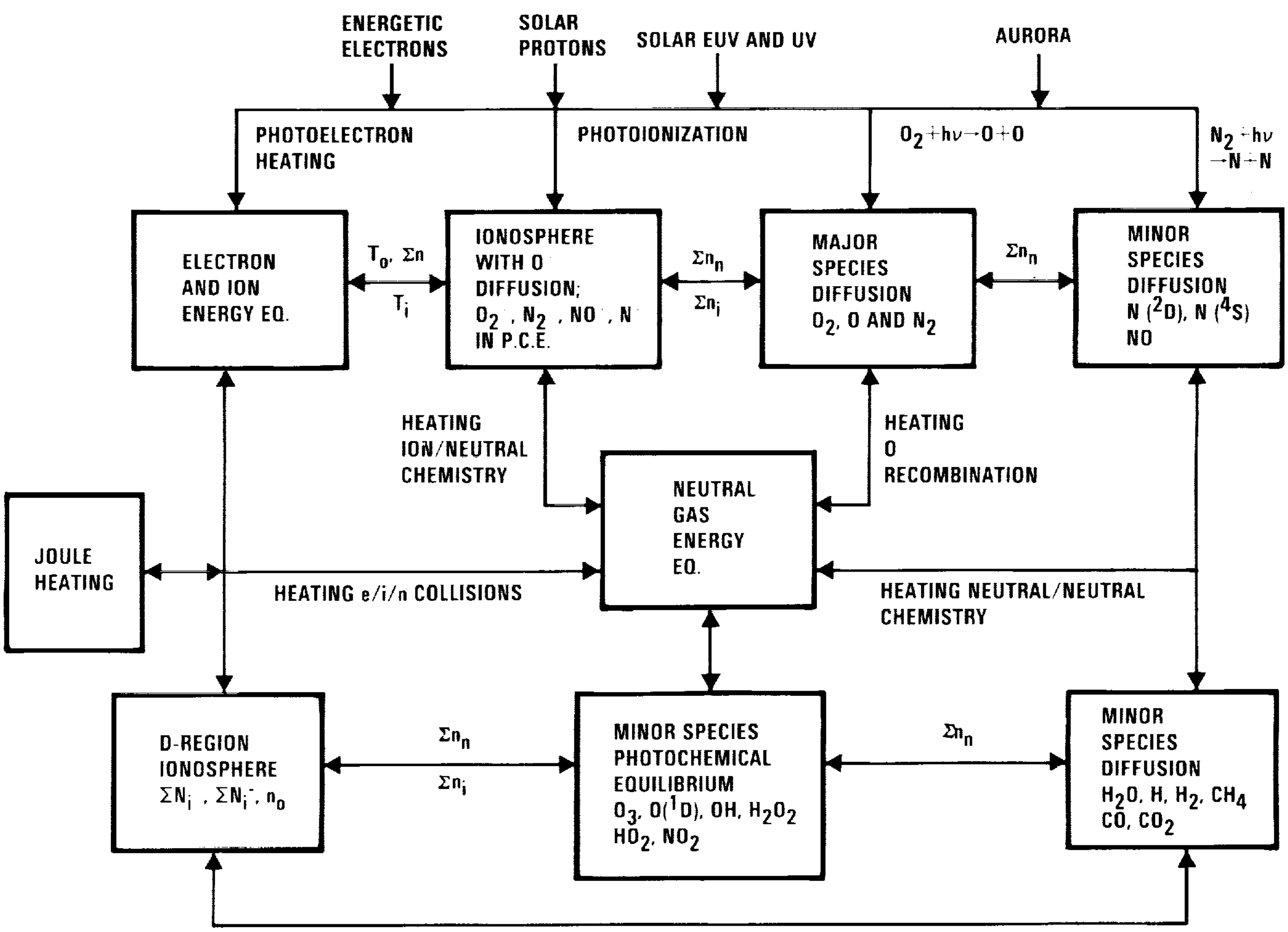

Figure 3-1. Diagram of Processes Operating in the Thermosphere and Mesosphere

- Basic structure of wind, temperature and composition
- Role of breaking gravity waves on energy and momentum budgets and as a mechanism for species transport
- Dissipation of upward propagating tides by molecular viscosity, thermal conductivity and ion drag
- OX, HOX and NOX chemical cycles and their response to solar radiative outputs, particle precipitation and disturbances from the lower atmosphere
- Role of nonlocal thermodynamic equilibrium infrared radiation from CO_2 and NO as cooling mechanisms.

The broad question of the chemical, radiative, and dynamic response of the mesosphere/lower thermosphere to solar and auroral variability is not well understood and experimental and theoretical studies should be made. The neutral winds in the region need to be measured in a global sense to guide modeling efforts with better measurement constraints. The basic structure of the temperature, composition and dynamics fields need to be defined to provide a baseline against which modifications from the increasing CO_2 burden can be evaluated.

3.3.2 Thermosphere/Ionosphere/Magnetosphere Interactions (<200 km)

A series of spacecraft programs, including OGO-6, AE-C, AE-D, AE-E, and the Dynamics Explorers, together with ground-based and other related observations have provided the data necessary to define most of the large scale processes operating in the upper atmosphere. Theoretical and numerical models have also been developed to provide a quantitative description of the region and its variability. The advanced state of our understanding notwithstanding, there are still a number of critical aeronomic processes that are highly parameterized because of a lack of the fundamental measurements that are needed to adequately describe them. Solutions to these problems could come from advanced measurement capabilities and increased insight into the nature of the region. It would be possible to significantly advance the state of knowledge of the interactions of the magnetosphere with the ionosphere and atmosphere while simultaneously complementing the International Solar Terrestrial Physics Program (ISTP). An advanced Explorer class aeronomy satellite will provide the observations necessary to describe the region that is the sink for most of the processes being investigated in the ISTP. This is a mission that begs to be undertaken.

Such a mission could be designed to answer several fundamental aeronomic problems, e.g., $N(^2D) + O$ quenching, $O + CO_2$ vibration excitation, and IR cooling. New instruments developed since the last flight opportunities should provide increased capability to resolve the fundamental aeronomic problems. Refinements in our understanding the chemical, radiative, and dynamical processes and their dependence on solar variability are needed and could be obtained by sophisticated instruments applied in effective measurement strategies. Altogether, a substantial scientific return would accrue from a modest mission that returns to the thermosphere during the epoch of ISTP.

3.3.3 Global Electrodynamics

The global electric circuit consists of three separate but interacting generators: (1) global thunderstorms maintain an Earth/ionosphere potential of 10^5 volts with a current of 10^3 amperes; (2) the ionospheric wind dynamo generates a potential of 10^4 volts with a current of 10^5 amperes; and (3) the solar wind/magnetosphere dynamo generates a potential of 10^5 volts and a current of 10^6 amperes. Understanding this global electric circuit is fundamental to atmospheric science and an integrated study of the total process is indicated. The study must include investigation of the relationship of the thunderstorm and lightning to upper atmospheric phenomena and include mapping of electric fields from thunderstorms to the ionosphere, from the ionosphere to the surface of the Earth, and between magnetosphere and ionosphere. The interaction of the neutral gas with the plasma and the resultant electrodynamic processes need to be quantified; new mapping procedures that incorporate disparate data sets can be of particular value in defining the morphology of the electrodynamic process which, through the use of models, can advance understanding of this interesting and complex phenomenon. Finally, the dependence of the global electrodynamics processes on solar variability must be understood.

3.3.4 Fundamental Process Measurements in the Space Environment

During the evolution of a scientific discipline, it inevitably becomes possible to pose questions of increasing detail and sophistication and it becomes necessary to attempt measurements of greater precision. In the recent past, exploration of the upper atmosphere has lagged behind the theoretical and associated modeling activities and has not exploited the latest technology available for space application. Atmospheric models require a large number of input parameters, and at the pioneering stage only a few of these are known. As the field matures, more parameters are known with better precision, but inevitably some are more poorly known than others. The experiment becomes an exercise in determining those least well known. This of course does not provide an adequate test for the model—what is needed is an overdetermined set of parameters, with sufficient accuracy. Whereas in the past, measurements with 50% accuracy could advance our knowledge, now the requirements may be for accuracies of 10% or better. It is, thus, possible to envision experimental programs that would advance our state of understanding through more precise quantification of states and processes through application of advanced remote and in-situ techniques. Some outstanding examples are:

- Solar, airglow and infrared radiation fluxes
- Excited and metastable species concentrations
- Ion/neutral and neutral/neutral rate constants
- Absorption and collisional cross sections.

Technological developments now make possible these more comprehensive and accurate measurements. In the optical field, array detectors provide vastly more efficient collection of spectral and spatial information. In terms of sources, fluorescence lamps, particle beams, and lasers provide excellent potential for active measurements. The optical field can be used in the local or remote sensing mode. The latter is practically the only way the mesosphere can be explored, but novel platforms such as the tethered satellite could be used to great advantage. A concerted effort to better define these and other fundamental attributes of the upper atmosphere in the actual thermosphere and ionosphere environment by in situ and remote measurements should be an important part of future exploration and could effectively exploit new technology and advanced spacecraft and missions.

3.4 Missions and Platforms

The outstanding scientific problems in the upper atmosphere can and must be studied by a wide range of remote and in-situ measurements, by missions to existing data bases, and through continued theoretical and modeling studies. The measurements could be provided by a variety of spacecraft—indeed, there is application for the full arsenal of planned platforms including space station, the polar platform, and tethered satellites—but the platform of choice tends to be Explorer-type free flyers where the science can fully drive the mission scenarios and where the perturbation environment is in the hands of the investigator. Table 3-1 shows, in a very simplistic way, how various platforms satisfy the needs of the experiments that would be undertaken to solve the scientific questions that have been posed. The spacecraft of choice is indicated by the double X.

Table 3-1. Applicability of Platforms to Experiment

Platform / Science Goal	Lower Thermosphere & Mesosphere	Global Electro-dynamics	Detailed Understanding of Thermosphere	Fundamental Aeronomic Processes
Space Station				
Attached Payloads		X		X
Polar Platform	X		X	
Co-orbit Platform			X	
Tethered			X	X
Man-Tended				XX
STS				
Space Lab				
Tethered	X	X	X	
Explorers	XX	XX	XX	XX
Rockets	X	X	X	
Balloons		X		
Ground-Based	X	X	X	X

The optimal missions for studying the identified problems need to be (and are being) defined by the scientific community. Two missions that emerge clearly from even a superficial analysis of the state of understanding of the upper atmosphere are (1) a mission that would remotely sense the mesosphere and lower thermosphere, and (2) a mission of one or two spacecraft that would combine in-situ and remote sensing in the thermosphere that would be in orbit during the ISTP program. These latter spacecraft would employ on-board propulsion, as did the Atmosphere Explorers, to give them access to a wide range of altitudes and a long lifetime. These two missions, supplemented by the application of attached payloads, tethered satellite measurements, and ground based measurements, would fuel a vital scientific enterprise in the upper atmospheric discipline.

3.5 Summary

During the 1970s and 1980s the thermosphere was explored extensively with the Atmosphere Explorer satellites, with the Dynamics Explorer 2 satellite, and through supporting observations from rockets, balloons and ground-based instruments. A major increment in our understanding of the thermosphere resulted from the analysis of the data accrued through these observations, but, as in any such complex endeavor, new questions were posed by the data that have not yet been answered. The mesosphere and lower thermosphere have been less thoroughly studied because of the difficulty of accessibility on a global scale, and many rather fundamental characteristics of these regions are not well understood. Given these circumstances, together with the great power of today's models and the availability of new measuring technology, substantial gains in our understanding of the upper atmosphere can be envisioned as a product of a relatively modest investment in experimental investigations and associated theoretical and modeling studies. Moreover, the ISTP program shows a compelling need for simultaneous measurements in these regions to define the state of the ultimate sink for many of the energetic processes that will be studied in the ISTP. Through careful planning, a major defect in the ISTP measurement suite can be eliminated by a mission that would also address most of the outstanding problems in thermosphere and mesosphere science.

A wide variety of measurement platforms can be used to implement various parts of the measurement strategy, but the major thrusts of the program would require Explorer-class missions. A remote sensing mission to explore the mesosphere and lower thermosphere and one or two Explorer-type spacecraft to enable a mission into the thermosphere itself would provide the essential components of a productive program of exploration of this important region of the upper atmosphere.