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Committee on Solar-Terrestrial Research
Geophysics Research Board
Assembly of Mathematical and Physical Sciences
National Research Council

NATIONAL ACADEMY OF SCIENCES

Washington, D.C. 1979

NOTICE: The project that is the subject of this report was approved by the Governing Board of the National Research Council, whose members are drawn from the Councils of the National Academy of Sciences, the National Academy of Engineering, and the Institute of Medicine. The members of the Committee responsible for this report were chosen for their special competences and with regard for appropriate balance.

This report has been reviewed by a group other than the authors according to the procedures approved by a Report Review Committee consisting of members of the National Academy of Sciences, the National Academy of Engineering and the Institute of Medicine.

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PREFACE

This report contains the results of a study, carried out on behalf of the Committee on Solar-Terrestrial Research of the National Research Council's Geophysics Research Board, to establish the future role and directions of both ground-based and suborbital (rocket, balloon, aircraft) measurement techniques for upper-atmosphere research in the 1980's. The upper atmosphere, for the purposes of this study, is defined as the region between the stratosphere and the exosphere; magnetospheric research was not explicitly included. This report complements other studies carried out by a number of other committees and as such is part of an overall effort to develop a national strategy of solar-terrestrial research for the 1980's.

The study was conducted at Woods Hole, Massachusetts, on July 3-8, 1978, under the chairmanship of Francis S. Johnson. The participating scientists were selected to include theoreticians as well as experimentalists; a special effort was made to achieve a good and balanced representation among the participants for both remote sensing (e.g., optical and radio) and *in situ* measurement techniques. The recommendations of this study were presented to officials of the National Science Foundation and the National Aeronautics and Space Administration. This report was reviewed and endorsed by the full Committee on Solar-Terrestrial Research in October 1978, subject to certain minor modifications, which were later incorporated.

The Committee on Solar-Terrestrial Research wishes to take this opportunity to thank the participants of the study for all their efforts. Special thanks are due to Francis Johnson, whose patience and hard work made this report possible. Edward R. Dyer, Secretary of the Committee on Solar-Terrestrial Research, who served as staff officer for the study, and Helene Patterson are also acknowledged for their contributions to the report's preparation. The enthusiastic cooperation of the various agency program officials, especially Alan J. Grobecker, Dennis S. Peacock, and Herbert Carlson, all of NSF, and Shelby G. Tilford of NASA was invaluable. The Committee acknowledges with appreciation the support of the National Science Foundation, which helped to make this study possible.

Andrew F. Nagy, *Chairman*
Committee on Solar-Terrestrial Research

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EXECUTIVE SUMMARY

1.1 INTRODUCTION

Scientific Interest. The upper atmosphere is a region of great intrinsic scientific interest and considerable practical importance as a component of man's environment. In terms of basic science it represents a region of transition between the lower atmosphere, where fluid properties dominate, and the near vacuum of interplanetary space, which is dominated by a tenuous plasma and high-energy radiation. The upper atmosphere is the seat of a huge variety of physical phenomena, many of which involve complex interactions among fluid dynamics, radiative effects, and chemistry. It contains an electrically charged component--the ionosphere--which in itself encompasses a wide variety of plasma regimes. Historically the challenge of explaining upper-atmospheric phenomena has provided a stimulus for a great deal of basic scientific research that has ultimately found application in other fields. The interests of fundamental science hardly need further discussion.

Practical Importance: Three Examples. The intrinsic practical importance of the upper atmosphere has received widespread recent attention in connection with the ozone problem. While the importance of the ozone layer in protecting life on earth from harmful solar ultraviolet radiation has been appreciated for many years, its extreme fragility was recognized only after catalysts were identified that are very effective in destroying ozone and that are introduced into the stratosphere both by natural processes and by man's activities. The relative ease with which the ozone layer can be seriously damaged is now widely recognized, and the broad range of potential consequences for life on earth is receiving increasing attention. This has resulted in a virtual explosion in stratospheric research in recent years, and our knowledge of this hitherto neglected region of the atmosphere between about 15 and 50 km has increased substantially. Accompanying this increase in knowledge, however, has come an increasing appreciation of the complexities of the stratosphere and of the importance of the interplay among dynamics, radiation, and photochemistry. The increase in our knowledge of the stratosphere has led to an enhanced awareness of our ignorance of the mechanisms that couple the stratosphere to the troposphere and of our extensive lack of knowledge of the mesosphere (50-80 km) and lower thermosphere (80 to about 140 km), which are inacessible to both balloon and satellite *in situ* probing. (The ceiling for balloons is about 50 km, and the lower limit for satellites is about 140 km.) It is remarkable that we know so little about these regions of our atmosphere.

Although the ozone layer has provided the most dramatic instance of the practical importance of the upper atmosphere, other aspects exist. For example, the infrared properties of the upper atmosphere influence the overall radiative balance of the earth-atmosphere system and hence may have a direct effect on global surface temperatures. The possible existence of strong positive feedbacks in the coupling among dynamics, radiation, and chemistry may serve to amplify small perturbations in the system. For example, the global distribution of ozone is directly affected by stratospheric wind systems, which are themselves driven mainly by the geographical pattern of heating of ozone by absorption of solar ultraviolet radiation. The potential for feedback in a coupled system of this kind is obvious, and feedback may have an important role in the observed relationship between solar activity and weather, currently an area of widespread interest and speculation.

The electrically charged component of the upper atmosphere (i.e., the ionosphere) has considerable practical importance through its effects on radio communication. High-frequency radio propagation via ionospheric reflection still has a major role to play, particularly in lesser-developed countries and for certain applications in technologically advanced countries, and accurate estimates of ionospheric properties depend in an essential way on our knowledge of the upper atmosphere and its ion composition. High-frequency radio communication has tended to be replaced in recent decades by communication at still higher frequencies via satellite links. Even these links suffer from ionospheric effects, however, and severe distortion often results from scintillations induced by ionospheric irregularities. Long-range global navigation systems are dependent on low-frequency radio waves whose propagation is strongly influenced by the extremely complex D region of the ionosphere.

1.2 SCOPE OF THE STUDY

We did not study what might be done, or what should be done, with regard to atmospheric sensing from space, and we did not consider the problems or needs of magnetospheric physics nor of solar-terrestrial physics in general. These restrictions resulted from the time available to organize and conduct the study; had they not been applied, the scope of the study would have become so broad that only general conclusions might have been reached. Instead, it was felt worthwhile to proceed with the more limited study that could provide recommendations on the directions that should be taken for probing the atmosphere from the ground and with aircraft, balloons, and rockets in the 1980's. A companion study is planned for 1979 in the context of related studies, which will address the broader question of solar-terrestrial physics in general, including magnetospheric phenomena.

For the purpose of this study, the upper atmosphere was defined to include the neutral atmosphere above the level where weather is important--the troposphere, where there is a correspondingly large research effort--to as far out as interesting phenomena involving neutral particles occur, including the ionosphere insofar as it is closely linked with the neutral atmosphere. This is not to say that the troposphere, insofar as it interacts with the stratosphere, or acts as a source or sink of stratospheric processes, can be left out of account. The magnetosphere, the plasmasphere, and those aspects of the ionosphere that are interrelated only with the magnetosphere were not included.

Figure 1 illustrates the vertical thermal structure of the upper atmosphere up to about 400-km altitude. The lowest region, the troposphere, is the region in which weather occurs; although shown as extending only up to about 10-km altitude in Figure 1, its actual average height varies from about 8 km over the polar regions to 16 km over the equator; at middle latitudes the height

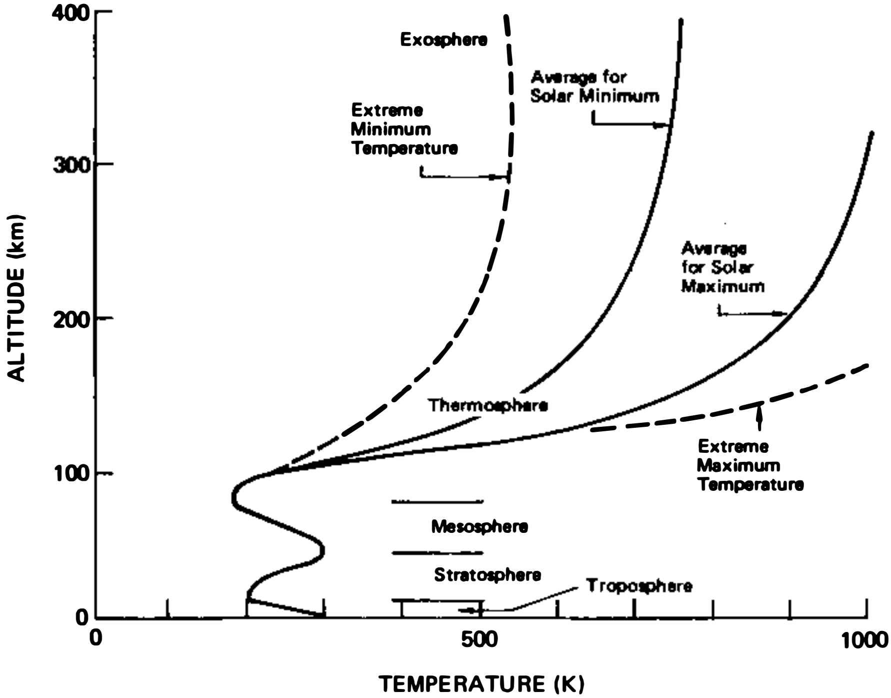

FIGURE 1 The temperature distribution through the atmosphere provides a basis for dividing the atmosphere into layers or spheres. The troposphere generates weather phenomena. The stratosphere is the location of the ozone layer. The exosphere is the outermost portion of the atmosphere where the gas is so rarified that collisions between gas particles occur only rarely, causing the temperature distribution there to be isothermal with height. Average curves for the thermosphere are shown for the maximum and minimum of the sunspot cycle. The dashed curves indicate the extreme temperatures occasionally encountered.

varies on a day-to-day basis according to the weather patterns. The troposphere is separated from the region above, the stratosphere, by the tropopause, where the temperature at low latitudes especially has a minimum value. The stratosphere is bounded on its upper side by the stratopause near an altitude of 50 km, where heating by absorption of solar ultraviolet radiation by ozone causes the temperature to have a maximum value. Above the stratosphere, the mesosphere extends from 50- to about 90-km altitude, where the temperature has another minimum value. The thermosphere extends from 90 km to much higher levels; because of absorption of solar extreme ultraviolet radiation and x rays it is a region of increasing temperature, finally reaching constant temperature with increasing height above about 300 km. The exosphere, a region in which the atmosphere is so rarified that collisions between atmospheric particles seldom occur, extends roughly from 500-km altitude on upward. Throughout the region above the troposphere, the atmosphere is very stable and resistant to convection, and vertical velocities are very much less than horizontal velocities except for small-scale motions associated with waves or turbulence. Even the mesosphere, where temperature decreases with altitude, is stable, because the rate of temperature decrease with altitude is much less than the critical adiabatic rate at which convection commences.

In recent years, the term "middle atmosphere" has been increasingly applied to the stratosphere and mesosphere taken as a unit, because they have much in common. The term is used in this report when it is convenient to treat the two regions together. (Obviously, our definition of the "upper atmosphere" includes the middle atmosphere.)

1.3 THE OBSERVATIONAL PROBLEM

For many atmospheric problems, the atmosphere must be regarded on a global basis; others must be examined on smaller scales. This gives rise to an observational difficulty because of the scale of the phenomena under investigation; even small-scale problems in the upper atmosphere are relatively large-scale ones compared with laboratory problems. These difficulties of scale are greatly magnified by the complications of atmospheric chemistry, which involves many constituents at extremely low concentrations.

Satellites provide ideal observing platforms for obtaining a global view of the atmosphere, although only on an intermittent basis. For some problems, this intermittency proves no disadvantage at all, but some phenomena require more-continuous observations than can be obtained from satellites. The other limitation that exists in satellite remote sensing of the upper atmosphere results from the nature of remote sensing; except for radar and lidar, the observations represent average conditions over considerable path lengths in the atmosphere. For some types of observations this property of averaging is an advantage, but it is most often a limitation, especially when observing small-scale phenomena. In this study we have not considered the matter of satellite observation of the upper atmosphere or made any recommendations in this regard. In considering what should be done from the ground, aircraft, balloons, and rockets in the 1980's we have assumed that there would be programs of atmospheric sensing from space and that the observations that can best be made from space platforms will be available.

Ground-based observations of the upper atmosphere must, of course, be accomplished by remote-sensing techniques, and these are subject to the same limitations as if they were applied in space. However, some of the recommended ground-based techniques (e.g., radar) have the advantage of providing continuous soundings at geophysically important locations. Other ground-based sensing techniques are relatively inexpensive, and the recommended applications are in areas where the property of averaging over substantial path lengths is not a limitation. The strong points of ground-based remote sensing are the capability for continuous measurements, the great versatility of radar measurements (involving an amazing array of physical properties of the atmosphere over relatively limited volumes), and the relative ease (and associated low cost) with which many optical measurements can be made.

Measurements from aircraft, balloons, and rockets complete the array of available techniques for upper-atmosphere research. These provide the only means of making *in situ* measurements below satellite altitudes. They are essential for making measurements of atmospheric composition in the case of constituents that cannot be sensed remotely. Moreover, *in situ* measurements are required to calibrate and establish the validity of some remote-sensing observations, and they will be needed to add detail beyond that which can be observed remotely. Coordinated measurements from satellites, rockets, balloons, and the ground will provide a more complete description of atmospheric regimes than can be obtained from the various measurements when they are made independently.

1.4 SUMMARY OF CONCLUSIONS

Many programs of upper-atmospheric research now exist. The recommendations presented here for new initiatives are based on our awareness of ongoing efforts in existing programs, the expectation that these programs will continue as appropriate, and our belief that some areas not now being pursued are ripe for attack, whether because of the development of new instrument capability, the inadequate exploitation of existing instrument capability, or the development of new theoretical insights that require testing. The principal recommendations are summarized in this section, not necessarily in order of priority.

1.4.1 Radar Study of the Troposphere, Stratosphere, and Mesosphere

Incoherent-scatter radars are exceedingly powerful instruments for observing the upper atmosphere, and important results have been obtained with radars at key locations on the earth's surface. Some unique and important regions remain unexplored by this technique. One is a subauroral location to examine disturbances emanating from the auroral zone or polar cap. *We recommend that an incoherent-scatter radar facility be established for the observation of a variety of important upper-atmospheric phenomena such as thermospheric winds and ion flows over a range of subauroral latitudes*. This could be accomplished by operating a receiver and antenna in coordination with an existing radar, to permit operation in the bistatic mode (i.e., to view the ionosphere from two directions and over a greater range).

To measure the important energy and momentum sources of the upper atmosphere at the "throat" of the auroral-zone convection pattern, where a major heat input exists, *we recommend that various options be explored for making incoherent-scatter radar observations at geomagnetic latitude $\Lambda = 76-78°$ and that an appropriate observatory be established at the earliest opportunity*. The "throat" is the location in the auroral oval near local noon, where electric fields and the associated plasma convection are especially strong. The recommended observatory would also be of great importance for magnetospheric research; however, as our study did not include that aspect of solar-terrestrial relations we give no justification from that point of view.

Radars operating in the coherent-scatter mode also have a great observing capability for atmospheric problems. The echoes in this case are believed to be due to turbulence or remnant variations in temperature or composition that were caused by earlier-existing turbulence, and they are characteristic of the neutral atmosphere. *We recommend that efforts be made to exploit mesosphere-stratosphere-troposphere (MST) radar capability at midlatitudes,* where it would be of special value in studying stratosphere-troposphere exchange and transport properties in the stratosphere and mesosphere by sampling as feasible in a few places. An economical way of accomplishing this would be by upgrading existing VHF radars by enlarging the antenna area. We are pleased to note the development of another type of radar capability, the stratosphere-troposphere (ST) radar, which should be of great value in investigating phenomena in the troposphere and lower stratosphere (up to about 30 km), such as mountain waves and clear-air turbulence. *We recommend that the newly demonstrated capabilities of the ST-radar technique be exploited using existing instrumentation in order to gain a fuller understanding of the importance of small-scale motions to the overall dynamics of the upper troposphere and lower stratosphere. Studies should be undertaken to examine the potential scientific return of a more extensive network of ST radars. Preliminary design studies of a transportable ST radar should be undertaken in order to establish the specifications and cost of an ST radar network.*

1.4.2 Optical Measurements

Rapid advances have been made in recent years in optical devices and detectors, and these present the opportunity for a great improvement in the capability of instruments used for remotely sensing properties of the upper atmosphere. *We recommend that advances in optical technology recently developed for use on spacecraft be exploited by further development and upgrading of instrumentation for ground-based studies of the energy sources, chemistry, and dynamics of the upper atmosphere.*

1.4.3 Rocket and Balloon Measurements

Some payloads previously flown on balloons and rockets will be flown on the Space Shuttle when that system begins operating. However, many problems will remain for which this substitution will be impossible, and there will remain a need for *in situ* measurements in the atmosphere. Even at satellite altitudes, a requirement for balloons and rockets will remain for investigations of small-scale phenomena or for situations for which measuring apparatus must wait in readiness until the correct geophysical conditions required for the investigation occur. *We recommend that the balloon and sounding-rocket program be preserved during the Space Shuttle era to make important atmospheric measurements that cannot be made from satellites. We further recommend the maintenance and, where required, the expansion of rocket and balloon launch facilities to accommodate the needs for data acquisition at various geographical locations.* Provision for fixed sites as well as the capability for campaign operations should be made.

1.4.4 Chemistry and Transport

A promising start has been made during the past few years on the study of the chemistry and large-scale quasi-horizontal transport processes in the stratosphere. In large measure this work has served to expose our ignorance of this important and neglected region of the atmosphere, the one most closely coupled to the lowest portion in which we live. *We recommend that the momentum now established in stratospheric investigations be vigorously maintained. To do this we need to exploit present methods of both* in situ *and remote sensing of chemically active minor constituents and to develop new methods. We also strongly encourage study and development of methods, particularly those using tracers, for examining the global-scale horizontal movement of air masses within the stratosphere.*

Knowledge of the concentrations of minor species in the mesosphere is very limited. The photochemistry of this region should be relatively simple compared with that of other regions. Yet the few existing measurements of such mesospheric species as OH, NO, and to some extent O_3 are in strong disagreement with theoretical predictions. It is important that the photochemistry and composition of the mesosphere be understood if we are to hope to understand more complex regions. *We recommend that a program be undertaken to determine the distribution of mesospheric constituents. Relevant photolysis rates should also be measured.* Instruments carried on parachutes dropped from sounding rockets in the neighborhood of 90 km may provide improved measurements of species such as O, O_3, OH, HO_2, H_2, CO, and NO.

Exchange processes between the troposphere and the stratosphere are not well understood, although they control the introduction of pollutants from the troposphere into the stratosphere and the removal of radicals and radical reaction products from the stratosphere to the troposphere. *We recommend that more observational and theoretical studies be devoted to the stratosphere-troposphere interchange process and that fast-response instrumentation be developed for measurements of chemical constitutents such as O_3, H_2O, and CO in support of these studies.* *In situ* measurements on balloons and aircraft, ground-based radar, and/or lidar measurements on aircraft will be needed.

1.4.5 Electric Fields

Electric fields within the atmosphere have emerged in the last few years as a potentially important coupling mechanism between the upper and lower atmosphere. Ways in which this electrical coupling can influence the dynamics are not clear, but the absence of other recognized mechanisms elevates the probable importance of this coupling. It therefore appears that the time is right for a more systematic and larger-scale attack on the problem. *We recommend investigation of atmospheric electric fields of magnetospheric, ionospheric dynamo, and thunderstorm origin to determine their role in middle atmospheric transport and chemical processes.* This will require a program involving balloons and rockets.

1.4.5 Other Recommendations

In addition to the above recommendations, a number of recommendations are made concerning other continuing and/ or increased activities. These are found in Chapters 3-7 of this report (together with more detailed treatment of those just described) and are not summarized here.

A list of the recommendations appears in Table 1.

TABLE 1 List of Recommendations

With atmospheric regions and scientific areas of interest to which each recommendation is applicable. The numbers refer to the Sections in Chapters 6 and 7. A key to the symbols will be found at the end.

Regions	Scientific Areas	Section	Recommendation
Th	DE	6.1	Subauroral incoherent-scatter thermospheric wind observations
Th	DE	6.2	High-latitude Magneto-spheric/Atmospheric Dynamics Observatory
TrSM	D	6.3	MST and ST radars
Th	CDE	6.4	Application of new optical technology to upper-atmosphere studies
UMTh	D	6.5	Meteor-wind radar
Th	D	6.6	Airglow measurements of F-region winds
MLTh	D	6.7	Partial reflection drifts and lidars
Th	D	6.8	Plasma irregularity and instability studies
Th	CDE	6.9	Active experiments
TrSM	D	6.10	Dynamical studies of the middle atmosphere at Jicamarca
SM	C(DE)	6.11	Measurement of trace constituents by high-resolution spectroscopy
SM	C	6.12	Infrared ozone total-column measurements
M	C	6.13	Airglow determination of O_3, H, and O distributions
Th	CDE	6.14	Airglow studies of thermo-spheric and exospheric processes
TrS	C	6.15	Archiving of infrared solar spectra obtained within the atmosphere
S	C	6.16	Data management for strato-sphere chemistry and aerosols

TABLE 1 (continued)

Regions	Scientific Areas	Section	Recommendation
All	All	6.17	Clustering
All	CDE	7.1	Sounding rockets and balloons and their launch sites
SM	CD(E)	7.2	Stratospheric and mesospheric composition and photochemistry
TrS	CD	7.3	Stratosphere-tropospheric exchange
All	D(E)	7.4	Planetary electrodynamics
M	C	7.5	Mesospheric ion composition
LTh	CD	7.6	Chemistry in the lower thermosphere
MLTh	CE	7.7	Mesosphere and lower-thermosphere disturbances
All	All	7.8	Maintenance of the meteorological rocket network
TrS	C(DE)	7.9	Sources of important stratospheric reactants and IR active gases
S	C(E)	7.10	Measurement of stratospheric aerosols
SMLTh	(C)E	7.11	Measurement of direct and scattered solar ultraviolet radiation within the upper atmosphere

REGIONS:
Tr, troposphere. (The troposphere as such is not covered in this study but is mentioned in only those recommendations in which its interaction with the stratosphere is involved or in which the technique in question obtains information on the troposphere incidental to information on higher regions.)
S, stratosphere.
M, mesosphere.
Th, thermosphere.
U (upper) and L (lower) apply only to the symbol immediately following.

SCIENTIFIC AREAS:

C, chemistry.

D, dynamics.

E, energetics.

Since these factors are not really separable, a single symbol indicates the primary area of interest, although the recommendation may well have implications in the other areas as well. A symbol in parentheses indicates that the implications for that area are discussed in the text accompanying the recommendation, although the area may not be explicitly mentioned in the recommendation itself.

Recommendations of a more general nature appear in Chapters 3-5.

2

THE NATURE OF THE PROBLEMS

2.1 INTRODUCTION

For many atmospheric problems, it is necessary to acquire observations distributed over the entire globe, or at least over a hemisphere. Examples are the large-scale circulation of the atmosphere and the problem of trends in the total amount of ozone. The real nature of the atmospheric circulation cannot be perceived or analyzed without a distribution of observations over a hemisphere, and ozone observations at a single point are inherently incapable of establishing the reality of small trends because of the magnitude of local variations. An ozone observing network covering the entire earth would provide a means of evaluating the total ozone in the atmosphere and would be capable of detecting small trends over a period of a few years. The distribution of land and water, however, makes it impossible to establish such a uniform network and to maintain it for a period of years; as a consequence, small changes in global total ozone cannot be recognized from ground-based observations.

Satellites provide the optimum platform from which to gather data on a worldwide basis, at least to the extent that suitable observing techniques exist. Even when a satellite-based observing technique is less precise than desired, the global acquisition of data may more than compensate for the relatively poor resolution of the observations. Thus it is necessary to look to satellites to obtain data on an extensive basis even when only a limited observing capability exists; when good capability exists, satellites can provide the ultimate in observation on a global scale.

Many of the problems presented by the atmosphere, however, can be addressed only by the use of *in situ* techniques, especially when global coverage is not the prime consideration or where suitable techniques for remote sensing do not exist. Such problems include the measurement of small-scale variability (i.e., parameters varying in space or time on scales smaller than the capacity of remote-sensing techniques to resolve), the testing of chemical reaction schemes, and the study of temporal variability at a single location; none of these is amenable to remote sensing from spacecraft. Balloons are useful in establishing or verifying circulation patterns derived from remote-sensing measurements or other sources. Aircraft are required for studies involving mobile platforms, such as the important problem of troposphere-stratosphere interchange and tropopause-folding events. Over the next decade, the use of rockets will remain essential in those areas where there is no reliable alternative to *in situ* observation (e.g., in problems of neutral and ion chemistry of the ionosphere) and where rocket observations can complement ground-based and satellite techniques in providing continuity of observation throughout the atmosphere (e.g., in studies of global planetary electrodynamics). Rockets also have a vital role to play in certain active experiments, in new instrument development, and in *in situ* "truth" measurements for the validation of remote-sensing techniques.

2.2 COMPOSITION AND CHEMISTRY

2.2.1 Stratosphere

The chemistry of the stratosphere is exceedingly complicated, and the description of atmospheric composition must be very detailed in order to permit a realistic consideration of the chemistry. Whole families of substances of interest are present in the stratosphere in addition to the normal background of clean dry air; even though dry ("dry" is, of course, a relative term) a sufficient amount of water vapor is always present to affect the chemistry in important ways.

Among the substances of interest, probably the first that should be mentioned is odd oxygen--atomic oxygen O, ozone O_3, and excited atomic oxygen $O(^1D)$ that arises from the photodissociation of O_3 by solar ultraviolet radiation with wavelengths shorter than 310 nm. Next are the radicals NO, NO_2, OH, HO_2, Cl, and ClO. These constituents, plus a few other chemical forms, are at times referred to as odd N, odd H, and odd Cl because within each family chemical forms transfer relatively rapidly from one to another. The radical precursors--the constituents from which radicals arise through photochemical reactions--include N_2O, CH_4, CFM's (chlorofluoromethanes, often known under tradenames such as Freon), CH_3Cl, other halocarbons (including bromine compounds), COS (carbonyl sulfide), and water vapor; these are the relatively stable source molecules that are introduced into the troposphere and gradually enter the stratosphere. Another category of interest consists of radical-radical reaction products, which are generally inactive as catalysts but which constitute a form of storage from which radicals can be released photochemically; these include such species as HCl, HNO_3, $ClONO_2$, H_2O_2, HO_2NO, and HOCl. Constituents that are important in the formation of aerosols include SO_2, COS, NH_3, and H_2SO_4. Carbon compounds CO and H_2CO are also of importance to stratospheric chemistry. This provides an impressive array of constituents whose concentrations must be known, along with their distributions in altitude, latitude, and time, just to describe adequately the composition and structure of the stratosphere. The concentrations of all of these constituents are very small (typically parts per billion or less), and sophisticated measuring techniques are needed to observe them.

The processes of interest are also numerous and in many cases difficult to observe. These include the generation of the source gases--the radical precursors--by biological or physical processes at the earth's surface, the removal of gases and particles from the troposphere (i.e., tropospheric sinks), the photochemical reactions of the stratosphere (and in some cases the troposphere), aerosol formation, heterogenous reactions that take place on the surfaces of aerosols, radiative effects of gaseous constituents and aerosols, and atmospheric transport. In an oversimplified view of the problem, source molecules generated at the earth's surface mix through the troposphere and are slowly transported into the stratosphere where they are converted into chemically active species--radicals--by photochemical reactions. However, some of the source molecules may be removed by sinks in the troposphere, reducing the number that eventually reach the stratosphere. Many radicals that are released in the stratosphere participate repeatedly in catalytic reactions, but some of them get converted into inactive forms--those radical-radical reaction products that provide a form of storage. There is a steady slow transport of the inactive forms back into the troposphere, where they are generally removed from the atmosphere by rain. In this way a relatively steady state is set up, but many complications arise as a result of alternate paths that some of the constituents may follow. Furthermore, the application of chemistry to the problem is complicated by the nature of atmospheric motions; e.g., where substantial vertical motions are associated with wave motions, the chemical reactions may take place preferentially in regions of higher or lower atmospheric density than that at the level under consideration--something for which a calculational scheme has not been developed and is not yet in sight.

Atmospheric aerosols is a general term that has been applied to matter suspended in the atmosphere ranging in size from 1-nm molecular clusters to micrometer-size particulates. Those with radii greater than about 0.1 μm are optically active, while smaller particles scatter light in a molecular fashion. A considerable amount of research has been done on the larger aerosols over the last five years. The stratosphere has been found to be a rather stable reservoir for these particles. Since sedimentation is very slow, once they are in the stratosphere particles remain there for relatively long times. Typical lifetimes are of the order of one year, in contrast to a few weeks at most in the troposphere.

It is now believed that these aerosols are formed in the stratosphere by gas-to-particle conversion processes and that the major constituent is sulfuric acid (H_2SO_4). The processes result in the formation of a stratospheric sulfate layer of aerosol particles at about 20 km. Typical stratospheric concentrations of these particles range from 0.5 cm^{-3} to 10 cm^{-3}. The gaseous sulfur responsible for the eventual formation of sulfuric acid droplets is thought to be mainly sulfur dioxide (SO_2). Carbonyl sulfide (COS), thought to be a by-product of coal combustion, has now been measured in the 0.5 parts per billion (ppb) range in the troposphere, and theoretically it should not react substantially until it has diffused some 30 km into the stratosphere, where it is converted to SO_2 by photolysis. Thus, COS may be an important man-made source of stratospheric aerosol.

The problems of understanding and describing atmospheric chemistry and composition include the following:

1. The general problem outlined above of formulating and testing independent descriptions, for various species, of (a) sources and sinks, (b) reaction schemes, and (c)

transport, which becomes important when chemical time-scales become comparable with or longer than transport time scales (see also Section 2.4.1 below).

2. The general problem of acquiring detailed measurements with sufficient spatial and temporal resolution. Because of the size of the atmosphere, the seasonal changes, and the short-range variations associated with the meteorological behavior of the atmosphere, this is a large task but one that is necessary for a satisfactory description and understanding of atmospheric composition. It will be necessary for many years to proceed with less-extensive data, but the limitations that this imposes on understanding and predicting chemical changes that take place in the atmosphere must be recognized.

3. As a particular case of (a) under item 1 above, the determination of sources and sinks of tropospheric precursors of stratospheric radicals and aerosols. This often involves attempts to formulate global cycles and budgets and programs to measure global-scale distributions of the species.

4. As a particular case of (b) under item 1 above, the determination of a complete chemical reaction scheme in the stratosphere (sometimes also extending into the troposphere), including photolysis and reaction rates and possibly heterogeneous reactions (i.e., on the surfaces of aerosols). This involves verification by measurements that identify certain species and that establish spatial and temporal distributions of several important species and of radiation fluxes. It applies to aerosol formation as well as to homogeneous chemistry. Supporting laboratory experiments are needed on reactions of gases that form gaseous or condensed products, or both.

5. As a particular case of (c) under item 1 above, acquiring an understanding of transport of trace substances within the stratosphere and between the stratosphere and the troposphere. This involves intensive sampling and measurement campaigns with mesoscale resolution.

6. Understanding of the mechanisms of removal of important species from the atmosphere by precipitation scavenging and deposition at the earth's surface.

7. Determination of the radiative properties of aerosols.

8. Testing of models or component parts of models by observing behavior of certain species after perturbation by certain events such as polar-cap absorption (PCA) events, volcanic eruptions, and controlled releases.

9. Use of models for studying effects of chemistry and

transport on atmospheric physical properties, including both natural and man-made perturbations.

10. Understanding of ion composition and the role of ions in the atmospheric chemistry of the stratosphere, particularly in aerosol formation.

2.2.2 Mesosphere

By comparison with the regions above and below it, the mesosphere is believed to be characterized by relatively simple photochemistry. Atomic oxygen is produced by the photodissociation of molecular oxygen by solar ultraviolet radiation in the Schumann-Runge bands. Above 55 km, the atomic oxygen remains mainly in that form during the daytime, but there is a large diurnal variation as it converts to ozone at night. Below 55 km, the atomic oxygen formed by photodissociation of molecular oxygen mainly converts to ozone, even in the daytime, when it is subject to photodissociation. Recombination of O and O_3 to O_2 in this region of the atmosphere is believed to be accomplished by catalytic reactive chains involving H, OH, and HO_2.

There are few observations of O_3 in the mesosphere, and these few provide little reassurance that we understand or are able to predict the concentration of such an active species. In the tropics at night, the observed concentrations between 40 and 55 km are sometimes found to be 3 to 5 times larger than expected, and above 55 km the profile is not at all like that expected. A measurement made of NO at 70 km is about 20 times the amount predicted by theoretical models.

One would like to measure the concentrations of O_3, O, OH, H, HO_2, NO_x, H_2O, CH_4, and H_2 and the diurnal variations of these constituents. *In situ* measurements can be made with instruments suspended from parachutes ejected from sounding rockets. Remote measurements of O_3, NO, NO_2, H_2O, and CH_4 are now being made from satellites.

2.2.3 Thermosphere

There are still no direct measurements in the lower thermosphere of chemically active species. Atmosphere Explorer measurements did not extend below 150 km. A fundamental factor that affects the structure of the thermosphere in a dominant way is the atomic oxygen distribution from 80 to 150 km. Measurements have been made with mass spectrometers in rockets, but recombination of oxygen on the surfaces of the rocket and spectrometer gives rise to questions about the validity of the interpretation of the measurements. Airglow measurements from above provide another means of obtaining the atomic oxygen profile, since recombination gives rise to green-line emissions that can be interpreted in terms of atomic oxygen concentrations. However, these observations have not answered the question of the atomic oxygen profile in a satisfactory way.

Another important question relates to the hydrogenous constituents in the lower thermosphere. Although CH_4 and H_2O provide the source molecules for release of atomic hydrogen and the escape flux from the top of the atmosphere is in the form of atomic hydrogen, the role of other species, particularly H_2, in carrying the upward flux needs to be established. Thus profiles of CH_4, H_2O, H_2, and H in the lower thermosphere are needed.

In the lower thermosphere and in the mesosphere, problems relating to the D region of the ionosphere remain, namely identifying and understanding the sources of ionization, the steps leading to the formation of the dominant ions (and even the identification of the dominant ions, especially in the case of negative ions), and the mechanisms leading to ion removal. Measurements made from sounding rockets, parachutes, and balloons are still required in order to clarify this murky situation.

The role of metals and metal ions in the lower thermosphere needs further investigation. Somewhat higher up in the thermosphere, Atmosphere Explorer has demonstrated the importance of metastable neutral and ion species in controlling the chemistry.

The upper atmosphere is strongly perturbed at certain times and in certain places by auroral precipitation, solar proton events, and planetary waves. *In situ* measurements of the energy input, the changes in neutral and ion composition, and the radiative balance at these times remain a requirement. Measurements made from sounding rockets, assisted by ground-based observations of optical phenomena, remain the most suitable method for attacking this class of problems.

2.2.4 Exosphere

The current belief is that escape of hydrogen from the exosphere is dominated by nonthermal escape, principally charge-exchange collisions between energetic hydrogen ions and hydrogen or oxygen atoms. However, there has been no direct observational confirmation of this concept. Ground-based observations with new high-sensitivity optical instrumentation may provide some of the necessary information.

2.3 ENERGETICS

2.3.1 Middle Atmosphere

The term middle atmosphere is used here as encompassing the stratosphere and mesosphere. In the 1980's we can expect substantial progress in the formulation and solution of three-dimensional time-dependent models of atmospheric dynamics and electrodynamics through the middle atmosphere. The success of these models will depend in part on the availability of data on the energy budget of the system, energy input at various altitudes, radiative energy transfer, chemical storage of energy, and energy transport by dynamical processes.

For the purpose of identifying measurement techniques, it is useful to consider two categories of energetics: the quasi-steady sources and those sources that are sporadic or of limited spatial extent. Satellites are optimal platforms from which to make global measurements of energy input into the thermosphere. For many purposes global coverage may be more important than the greater precision that may be obtained by other techniques. On the other hand, to evaluate quantitatively the effects of man-made or natural perturbations on the composition of the middle atmosphere, more detailed information is needed on the interactions of ultraviolet, visible, and infrared radiation with the gaseous constituents and atmospheric aerosols. It becomes clear that satellite observations must be supplemented and complemented by balloon, aircraft, and ground-based measurements. The quantities to be measured include the spectral distribution of the solar and terrestrial radiation field as functions of altitude, location, and season; the albedo of the underlying earth-atmosphere system; and the spatial distribution of radiatively active constituents such as O_3, H_2O, and CO_2 and of aerosol particles.

Of the many problems and unknowns in the middle-atmosphere radiation budget, we highlight one that presents a large uncertainty in calculating rates of atmospheric heating. Our present knowledge of the optical properties of stratospheric aerosol particles leads to about an order-of-magnitude uncertainty in deriving stratospheric heating rates caused by the presence of aerosol particles, and uncertainties in the sign appear in evaluating the effect of particulates on global-average surface temperatures.

Aerosol particles are known to be located in the stratosphere in approximately the 15- to 25-km altitude interval with highly variable concentrations, especially following major volcanic eruptions. High concentrations of particles have also been found in other regions of the upper atmosphere, as documented by the presence of noctilucent clouds at the mesopause and by occasional reports of aerosol layers at intermediate levels. Significant effects on the energy budget of the atmosphere were associated with the increase in aerosol concentrations observed after the eruption of the volcano Mt. Agung in early 1963. Approximately a year after the eruption, for example, temperature increases of 6 to 8 K were observed near 20-km altitude throughout the equatorial region.

Information on the physical and optical properties of stratospheric aerosols has been obtained by impactors and particle counters carried on balloons and aircraft, by ground-based and airborne lidar observations, and by ground-based photometric studies of the sky at twilight. Two satellite sensors (SAMII and SAGE) will soon obtain data on the global distribution of aerosol particles using an occultation technique; these observations will provide vertical profiles of aerosol extinction coefficients. The radiative transfer models used to evaluate the climatic effects of these particulates require additional information of the particle size, shape, and complex refractive index in both visible and infrared wavelengths. The least known parameter is the value of the imaginary refractive index for visible radiation--the quantity that directly determines the amount of energy absorbed by the particle from the solar radiation field. Measurements of the optical properties of the stratospheric aerosols are needed to complement the extinction data to be obtained from the satellite sensors in order to improve our ability to evaluate the effect of the aerosols on the energy budget of the stratosphere.

A significant uncertainty also exists in our ability to specify the vertical distribution of the direct and diffuse ultraviolet radiation field. This is important not only for use in calculating the amount of energy absorbed by atmospheric constituents but also for use in photochemical calculations. Data on the spectral variation of the solar input outside of the atmosphere are available from solar sensors on orbiting satellite platforms. However, the vertical change in the direct and diffuse solar ultraviolet radiation as it propagates downward is specified by using empirical values in the models. The calculation schemes must be tested. *In situ* observations using instrumentation mounted on balloons and rockets to determine the direct and diffuse ultraviolet radiation fields are required for validation and improvement of the stratospheric models.

Energetic particles provide both a quasi-steady and a sporadic energy input to the upper atmosphere at high latitudes. Fluxes of energetic protons follow major solar flares, and the bulk of their energy is dissipated in the form of ionization, mainly in the mesosphere in the case of protons with energies less than about 30 MeV, and in the stratosphere in the case of higher energies. The total energy input during a solar-proton event can be significant in comparison with other upper-atmosphere energy sources; for example, the average energy input to the high-latitude stratosphere in the form of protons with energies greater than 30 MeV during the events of August 1972 amounted to 1×10^{-3} to 2×10^{-3} W m^{-2} for a duration of about 3 days.

In the middle atmosphere the ionization process is accompanied by dissociation of nitrogen and water vapor, leading to formation of a wide range of odd-nitrogen and odd-hydrogen compounds that can initiate catalytic chemical-reaction chains. The energy released in this way can far exceed the intial energy input from the particles themselves, since the catalytic chains effectively tap the storehouse of chemical energy in the upper atmosphere. The largest single component of stored chemical energy is contained in dissociated oxygen in the form of atomic oxygen and ozone. The catalytic action of NO_x and HO_x compounds has the effect of increasing the rate at which recombination of O_3 and O proceeds. The HO_x chain is most effective in the mesosphere, but it has a relatively short duration since the lifetime of HO_x is only of the order of a day at these altitudes. The NO_x chain is most effective in the stratosphere, and it may have a long-enduring effect since the photochemical lifetime of NO_x in the stratosphere is very long.

Major solar-proton events cause substantial perturbations in the energy budget of the middle atmosphere, but their relatively infrequent occurrence suggests that their contribution to the long-term average energy is small. Other contributions come from relativistic electron precipitation events and from the quasi-steady ionization due to cosmic rays and the energetic-electron background. The importance of these sources to the time-averaged energy budget has not been assessed but may well be significant.

One of the more exciting prospects in the 1980's is the possibility of realizing a better understanding of global electrodynamics. Electric fields are present at all height levels of the atmosphere and have a significant impact on the energy budget in the thermosphere. High-altitude electric fields have been shown to penetrate to stratospheric levels at which they perturb the global atmospheric electric potential distribution. On the other hand, electric fields associated with thunderstorms perturb ionospheric fields and currents. This mapping of electric fields is one of the few clear, almost instanteous, coupling mechanisms between upper and lower atmospheric processes. Our lack of knowledge of the interactive effects of thermospheric, mesospheric, and stratospheric electric fields and the possible coupling of high-latitude electric fields to middle- and low-latitude regions suggests that measurements be made on a global scale and for extended time intervals. Superpressure balloon platforms operating for extended periods at high altitudes are suitable for studying this phenomenon.

2.3.2 Thermosphere

Ultraviolet radiation from the sun provides an important and relatively steady heat input into the thermosphere; this input does vary with the solar cycle and produces the solar-cycle variation in exospheric temperature (see Figure 1). Shorter-term variations result from enhanced radiation associated with solar flares.

Heat input into the upper atmosphere from the magnetosphere constitutes another important heat source. It includes a quasi-steady component due to Joule heating and particle precipitation around the auroral oval that is present nearly all the time; this has been estimated at about 5×10^{10} W for average auroral activity conditions. During magnetic storms, the Joule heating and particle-precipitation energy-input rate can be an order-of-magnitude greater ($\sim 5 \times 10^{11}$ W). About an order-of-magnitude more energy than is deposited in the auroral zones goes into the injection of energetic particles that become trapped in the earth's magnetic field (producing a ring current), where it is lost at a rate roughly an order of magnitude slower than the rate of injection. Some of this energy, (perhaps 10 percent) is directly deposited in the middle- and low-latitude regions of the upper atmosphere (at a rate of about 5×10^{10} W) as the ring current decays. Energy can be directly deposited by ion and electron precipitation, heat flow from the ring current, and energetic neutral-particle precipitation. These quantities are poorly known. There is a need for more measurements of optical emissions, ionization production rates, electric fields, and electron- and ion-temperature gradients along the field lines to evaluate the auroral-zone energy inputs and their variation in local time, the transport process, and the middle- and low-latitude direct energy inputs.

ULF-VLF wave-induced precipitation of trapped energetic particles into the atmospheric loss cone constitutes an energy source for the thermosphere and mesosphere. Both coherent and incoherent waveforms are present in the magnetosphere, and they may precipitate particle energy fluxes that are orders of magnitude larger than the energy fluxes in the scattering waves. A variety of wave-induced effects occur both within and beyond the plasmasphere. These effects have not yet been well described in terms of the scattering-wave type, particle energies involved, and temporal and spatial characteristics. The problem is further complicated by the presence in the magnetosphere of VLF waves from communication and navigation transmitters and from power distribution systems.

In the 1980's, satellite and Shuttle-based techniques can play an important role in describing the particle inputs to the atmosphere associated with scattering by waves, particularly the quasi-steady effects. However, the important dynamic effects such as fast temporal variations will require observations of precipitation effects (and associated wave activity) from the ground and from balloon and rocket platforms. The appropriate instruments include photometers, x-ray detectors, riometers, magnetometers, and ULF-VLF receivers. Each of these techniques is currently undergoing improvements in terms of imaging capability. These improvements should be continued so as to provide the instrumental basis for mapping precipitation activity, supporting associated space experiments, supporting active wave-injection experiments, and evaluating man-made precipitation effects.

2.4 STRUCTURE AND MOTIONS

2.4.1 Middle Atmosphere

The principal energy sources of the middle and lower atmosphere are solar heating of the earth's surface and of the ozone layer. This leads to a structure in which temperature decreases with altitude through the troposphere, increases through the stratosphere to a maximum near 50 km, and decreases through the mesosphere, as is shown schematically in Figure 1. The north-south differential in the heating of the ozone layer due to absorption of solar ultraviolet energy, and the subsequent infrared emission to space from ozone, carbon dioxide, and water vapor, drives a global circulation that is characterized by a strong westerly (west-to-east) jet in winter and a strong easterly (east-to-west) jet in summer, centered at altitudes near 60 km. Thus, there is a strong annual periodicity in middle-atmosphere flow. Other notable periodicities in the flow are the quasi-biennial oscillation that is prominent in the lower stratosphere near the equator and the semiannual oscillation that dominates at higher levels in the tropics and in the polar regions. The source of the quasi-biennial oscillation is believed to be the alternate eastward and westward acceleration arising from vertically propagating tropical wave modes. The source of the tropical semiannual oscillation is more uncertain but is thought to lie in alternate eastward and westward accelerations arising from vertically propagating tropical wave modes and planetary-scale disturbances that have their sources in the winter troposphere. At middle and high latitudes, somewhat irregular oscillations with one- to three-week periods are seen in the winter flow. Also, there is the sudden stratospheric warming--a high-latitude phenomenon that appears during some winters.

These middle- and high-latitude phenomena are thought to be intimately connected with vertically propagating planetary waves that are evident on winter weather maps as large-scale undulations in the flow. The vertical motions that accompany these global flows are very small (on the order of 1 cm sec^{-1} or less). Synoptic-scale disturbances (those flows that are familiarly seen as migrating highs and lows on weather maps) are believed to play a much reduced role in the middle atmsophere compared with their role in the troposphere. However, observations are inadequate to settle this issue at present.

Atmospheric tides are global-scale motions that are driven by the sun and the moon by their thermal and gravitational influences with periods equal to integral fractions of a solar and lunar day. Tidal winds are observed to be comparable with prevailing winds in the upper mesosphere and lower thermosphere. Gravity waves are much shorter-period oscillations that are forced by auroral disturbances, severe weather, and shear instabilities, as well as by other means. The vertical propagation of gravity waves upward from the troposphere is thought to act as an appreciable energy and momentum source for the middle atmosphere and above.

True turbulence comes about in the atmosphere by instability in the large-scale flow as well as instability of tidal and gravity waves. The role, and indeed the source, of turbulence above the lower stratosphere is uncertain at this time.

A great number of constituents of the upper atmosphere have chemical time scales that are much greater than the time scales for transport. Examples are O_3 in the lower stratosphere and NO in the mesosphere. For these and other longer-lived constituents, consideration of dynamics must accompany chemistry to explain correctly the observed concentrations. Although transport of chemical constituents takes place in response to motions on a variety of time and length scales, global distributions of species are thought to be primarily the results of chemistry and planetary-scale motions with periods of several days and longer. Smaller-scale motions are important in several contexts, however. Perhaps, the most important of these is in determining the stratosphere-troposphere exchange of air that is thought to occur in frontal-scale processes associated with the upper-tropospheric jet stream.

Transport of heat and the compressional heating and expansional cooling that accompany vertical motions also play a significant role in determining the temperature structure of the middle atmosphere. Observations of structure and dynamics from satellite platforms provide the global coverage necessary for the study of large-scale phenomena. Aircraft measurements are appropriate for somewhat smaller-scale phenomena. Long-duration balloons act as tracers of dynamics (in some average sense) of the combined effects of large- and small-scale motions; and ground-based measurements that give continuous measurements are most suitable for the study of wave structures and turbulence. To study the full range of dynamics, a proper combination of all of these measurement techniques is required.

2.4.2 Thermosphere and Ionosphere

The circulation and temperature structure of the low- and middle-latitude thermosphere are primarily controlled by heating due to the absorption of solar EUV and UV radiation. Yet the structure established by solar radiant heating is frequently perturbed by thermospheric waves and changes in the mean circulation that are generated by auroral substorms and geomagnetic activity that propagate equatorward through this region. These perturbations are manifestations of the global redistribution of auroral energy that is deposited locally in the high-latitude thermosphere. Thermospheric dynamics is strongly governed by the magnitude of the high-latitude heating because the variations in this heating are so large.

Two processes appear to be important, namely, electric currents flowing at altitudes of 100 to 140 km and the precipitation of energetic particles. While the presence of the current can be detected from ground-based measurements of magnetic-field perturbations, the heating rate is best determined by direct observations of the ionospheric electric fields that drive them, together with measurements of the conductivity of the region in which they flow. These can be made from the ground only be means of incoherent-scatter radar.

With regard to the particle energy input, substantial knowledge of the spatial and temporal variation of auroral precipitation has been gained from ground-based optical and spacecraft observations. Local heating rates from these auroral processes can be much larger than solar EUV heating, with consequent major influence on the dynamics and composition of the thermosphere. A more widespread particle energy input occurs in connection with rare solar-proton events that engulf the polar cap and auroral zone.

As a consequence of the irregular way in which auroral heating occurs, the thermosphere is dynamically active and is in a constant state of agitation. Since the effective energy transport is meridional in the thermosphere, the existing incoherent-scatter radars (Millstone, Arecibo, and Jicamarca) that lie along the 70° W meridian can be used to study the equatorial progression of thermospheric waves and circulation perturbations that are launched at high latitudes. The data obtained by these and optical stations can be analyzed with the use of numerical models of thermospheric circulation and temperature structure. These studies will define the dynamic processes that are so important in the global redistribution of auroral energy throughout the entire upper atmosphere.

The influence of electrodynamical phenomena is more complex. As noted above, substantial electric fields are present in the thermosphere. The total energy input from these fields in the auroral zone and polar cap is comparable with those provided by the solar EUV (extreme ultraviolet) and auroral precipitation. A particular concentration of such energy release occurs within the "throat" region of the polar cleft, where large electric fields are continually present. At present, there is no way of obtaining direct information about the behavior of the cusp or polar-cap electric fields, currents, or energy dissipation on a day-to-day basis.

A second influence exerted through high-latitude electrical processes is the transfer of momentum from the ionospheric plasma to the thermosphere. Models of thermospheric dynamics indicate that this momentum source is of key importance for understanding the global behavior of the thermosphere during periods of magnetospheric disturbance. An incoherent-scatter radar located in a position to observe the cusp in the local noon sector and monitor the polar cap at all local times would be a powerful tool for making progress on this problem.

Several scientific studies have appeared in the last few years indicating a relationship between solar activity and tropospheric weather. Among these have been indications that high-latitude tropospheric circulations are affected by solar sector-boundary processes, that droughts in the United States occur in relation to the 22-year magnetic solar cycle, and that climatic changes have occurred coincident in time with secular changes in sunspot activity. The chain of reactions between solar activity and tropospheric weather remains obscure at this time. Suggestions of mechanisms to explain this relationship include the following: (1) Solar activity affects the E- and F-region electric fields that map down to the troposphere and thereby modifies the fair-weather field and influences weather in some unrecognized manner. (2) Solar activity drives motions in the auroral zone and thereby couples energy into the high-latitude troposphere. (3) Solar effects change the ozone distribution that influences the winds in the middle atmosphere and so changes the planetary-wave reflection characteristic of the middle atmosphere. Balloon observations of the electric fields at stratospheric heights in polar regions, together with radar observations of motions in the lower thermosphere, mesosphere, and stratosphere, appear capable of examining the first two of these mechanisms.

The lower thermosphere (90-150 km) is a region affected by thermospheric processes from above and tidal, planetary, and gravity waves from below. Since many species produced in this region like NO and O are long lived, they are affected by transport processes as well as by fast nonlinear chemistry. To understand this region it is necessary to determine the mean circulation and temperature structure as well as the response to changes in the tidal structure and changes produced by geomagnetic activity. That is, dynamics has an important role in determining the compositional structure, which in turn affects processes in the thermosphere above and the mesosphere below. Observations of tides by incoherent-scatter and meteor-wind radars have shown that these are variable both from day-to-day and over distances of 1000 km--apparently reflecting the influence of background winds in the mesosphere in coupling energy from the fundamental into higher-order modes. This greatly complicates the dynamics of the lower thermosphere and has made it difficult to establish the average tidal behavior. A concerted effort is needed during the next few years to achieve this.

Dynamical models of the global distribution of temperature, density, and composition are extremely useful for a number of upper-atmospheric studies, since they conveniently summarize the large-scale structure of the thermosphere. The growing collection of observed quantities should be used to periodically update and improve model performance. The pressure forces specified by these semiempirical global models of neutral temperature and composition can be compared with those deduced from incoherent-scatter radar, optical, and possibly satellite measurements of winds. These studies provide a consistent check on the longitudinal and latitudinal gradients of neutral temperature and composition within the semiempirical models, since these variations primarily govern the thermospheric wind structure. Particular emphasis should be placed on improving the time-dependent predictive capabilities of the models by including the effects of tides propagating into the lower thermosphere and the response to auroral heating.

Planetary and gravity waves launched by weather fronts and other sources in the troposphere or stratosphere appear capable of propagating into the thermosphere, where they dissipate their energy either by nonlinear or by viscous effects. While it seems unlikely that these phenomena can be incorporated into the models outlined above, their importance for creating motions in the thermosphere that give rise to significant heating and/or transport effects remains uncertain and must be explored.

The dynamics of the ionospheric plasma constitutes a separate but related scientific study to that of the neutral atmosphere. At thermospheric heights, electrons are set in motion only by electric fields. At midlatitudes these are generated by tidal winds that transport ions across magnetic-field lines and establish polarization electric fields, while at high latitudes electric fields are impressed into the ionosphere by the interaction of the solar wind with the earth's magnetosphere. Ions can be transported horizontally by winds at altitudes below about 130 km, but at greater heights winds drive them only in the magnetic-field direction. Above about 150 km, electric fields drive ions across field lines in the same direction as the electrons. These ion motions serve as tracers of winds and electric fields for the incoherent-scatter radar technique.

In the presence of strong density gradients combined with electric fields, ionospheric plasma can become unstable in the sense that small density perturbations grow, creating large density fluctuations. Several irregularity processes appear to exist, and under appropriate conditions they can combine to create large irregularities in the plasma density with scales of kilometers to centimeters. Using means such as the energy deposited in the ionosphere by a large high-frequency (HF) transmitter, it is possible to stimulate these irregularities artificially. Research on these phenomena contributes to the understanding of plasma processes in a way that is often difficult to achieve in the laboratory.

3

THE ROLES OF THEORY AND MEASUREMENT

The remarkable developments in physical science and technology that have been especially striking in recent history are directly attributable to a logical procedure that has come to be called the scientific method. Its steps consist of the formulation of a hypothesis or prediction based on available facts followed by the testing of that hypothesis with measurements of the relevant predicted physical quantities.

In practice, when this method is applied to problems with the level of complexity that one finds in the atmospheric sciences, one is never dealing with theoretical formulations that are directly comparable with the atmosphere. A mixture of theoretical approaches is then called for. There are the so-called mechanistic models in which many of the intrinsic degrees of freedom of the atmosphere are suppressed with two goals in mind. These are to make the problem tractable and also to formulate the theoretical model in such a way that the solution, once obtained, can be interpreted in terms of the physical processes that are involved. Then there are the more comprehensive large-scale numerical models in which many more physical processes are included in the formulation. Whereas the latter approach is eventually expected to yield the more realistic simulation, the mechanistic models still enjoy some distinct advantages over the more comprehensive models. For example, in some instances it is impractical to explore the dependence of model response on the model parameters in a comprehensive model. Also, the level of effort that is required to diagnose the physical workings of a comprehensive model can be great. Finally, it may sometimes be the case that there is not enough data coverage available to check aginst a comprehensive model. Nonetheless, the ultimate test of our physical knowledge is whether we can merge formulations of many physical processes into a comprehensive model whose output is found to behave in the same way as the atmosphere, both in morphology and in the manner of satisfying the physical balance requirements.

In deciding on various directions to be pursued, it is important that a proper research strategy be implemented, by keeping in mind our use of the scientific method. For example, calculations or measurements made simply to add incrementally to a body of noncontroversial knowledge should be given low priority; efforts should be concentrated instead on critical areas that provide increased understanding or improved ability to predict.

Thus, there is an ever-increasing need for effective and constructive interplay between theory and observation in our approach to a scientifically meaningful and socially useful understanding of the upper atmosphere. At present, this interplay in upper-atmosphere research is highly developed and is improving. Specifically, theories are being presented in terms of measurable variables, and measurement programs are being conceived to provide data to help in formulating and validating theoretical models that either are being developed or are planned for future development.

There are and inevitably will be stages during which the extant theoretical and computational capabilities are not adequate to interpret certain measurements, either because the theory has not been properly formulated or because the observed parameter has not been encompassed in the theory. Many observable features of atmospheric dynamics and of auroral displays are beyond our present understanding. Similarly, there are times when theoretical calculations begin to pull too far ahead of experimental capabilities, as was the case with the predicted existence of key stratospheric species in the mid-1970's. It must be understood that these seemingly illogical imbalances are inevitable; they are part and parcel of the scientific method, and they are usually redressed quickly.

Accompanying the need for even closer interplay or tighter feedback between theory and observation are healthy prospects for rapid progress in both. Powerful instruments are now in place, and others are technically feasible. Recent advances in electronics and optics have led to dramatically improved ability of radars, lidars, lasers, spectrometers, and resonance lamps to cover wider vistas with higher resolution. Breakthroughs in physical and analytical chemistry and plasma physics, for example, have not only been adapted quickly to upper-atmosphere research, but some breakthroughs have resulted from it. On the theoretical side we are now armed with faster, more-versatile digital computers and with new insight into numerical methods of finite differences, finite elements, and allied areas of applied mathematics, and--not least--an increased awareness of the principal inputs and mechanisms in upper-atmosphere behavior.

We recommend that a balanced program of upper-atmosphere theoretical and diagnostic studies be supported that consists of both simple mechanism-oriented and comprehensive numerical models so that there will continue to be a healthy interplay between theory and experiment in the 1980's.

4

LABORATORY MEASUREMENTS

Laboratory studies, in particular of chemical reaction rates and absorption cross sections, are extremely important to atmospheric science. They have and should continue to follow the new developments in both modeling and atmospheric measurements, trying to check the reasonableness of these developments. The two major areas in which laboratory studies will have an important impact in the next decade are (1) the rates and energetics of reactions and (2) spectroscopic data, i.e., wavelengths and line-intensity information.

Improved data should be obtained concerning the dependence of reaction rates on temperature and pressure, particularly with regard to the effects of hydration on radical reactions. Data for photolytic processes are often sparse or totally lacking, particularly photodissociation rates, their branching ratios, and the temperature and wavelength dependences of these processes. The chemistry leading to aerosol formation and growth is only poorly known. An effort must be made to understand this chemistry and that of the possible heterogeneous reactions that may take place on the surfaces of aerosols, particularly reactions of radicals like O_3 and HO_2. There are very few data available on the reactions of excited states of both ions and neutral species. There are requirements for such data for species of interest all through the atmosphere, but the information is particularly sparse for species of interest above 70 km.

Because of the dramatic improvement in the techniques used in spectroscopy at all wavelengths from microwave to UV, there is an especially important requirement for higher-resolution and more-accurate information on line positions and intensity data in this field. There now exist many absorption spectra of the atmosphere in the wavelength range from 3 to 15 μm that undoubtedly contain information regarding unknown species in the atmosphere as well as secular trends for some atmospheric gases. However, since many of the weak lines of the major atmospheric gases (CO_2, H_2O, CH_4, and O_3, for example) are not catalogued or measured, it is difficult to make a unique identification of minor species in the combined spectra. There is therefore a requirement for both experimental and theoretical work on the molecules of major importance in determining the IR spectrum of the atmosphere. After such information is available, a much more nearly complete reduction of infrared spectra should be possible.

A particular need for stratospheric research is the ability to obtain spectra at very long path lengths (many kilometers) and at low pressures and temperatures. There is no such cell in operation at present; low-temperature operation is defeated by convection currents that ruin the light beam. A facility incorporating a well-engineered long-path cell and the best available spectroscopic instruments would make a major contribution to our understanding of spectra and their application to atmospheric physics.

5

CORRELATIVE MONITORING OBSERVATIONS AND SECONDARY USE OF DATA

Upper-atmosphere and solar-activity monitoring observations are relevant to upper-atmosphere research, particularly as important correlative and supporting data to key experiments. These are in many instances obtained as a scientific service by institutions or groups not otherwise participating in upper-atmosphere research or else as essentially unfunded piggyback activities. For data from geographical areas outside the United States (including solar monitoring from other time zones), great reliance has to be placed on international cooperation and on the mechanisms of data exchange through the World Data Center system.

The relative importance to thermospheric and middle-atmosphere research of all the individual types of monitoring separately is difficult to establish. A broader survey of the solar-terrestrial-physics (STP) and the solar-physics communities on the needs for STP monitoring in the 1980's is being conducted. The early responses indicate that STP monitoring activity provides many essential data, and the following data types were mentioned in particular:

(a) Auroral imagery, from the Defense Meteorological Satellite Program (DMSP);
(b) Polar-cap absorption (PCA) data;
(c) Asymmetric ring-current indices (*DS*).

It is important to achieve a condition of stable funding for approximately the present level of monitoring, followed by modest upgrading to bring monitoring techniques closer to the state of the art, possibly with modest extensions. Solar-flux-variability monitoring is being initiated under several satellite programs, and this will provide data essential to the understanding of the energetics and structure of the upper atmosphere.

Funding agencies should consider proposals for monitoring work in a category of "scientific services" somewhat distinct from research project proposals, and they should be reviewed accordingly. Care should be taken, however, not to perpetuate outmoded techniques or continue monitoring programs without major current or long-time-series justifications.

NOAA is urged to participate in the support of monitoring efforts essential to STP research generally in addition to those needed for the present techniques of solar-flare and geomagnetic forecasting and warnings, since future improvements in these application programs as well as the evident need for "meteorological services" in the 1980's for the middle atmosphere will depend on the success of these efforts. This responsibility seems to lie directly in the NOAA mission; certainly no other agency has this central responsibility.

The role of data exchange and the secondary or multiple use of many kinds of data are important. Many kinds of data should be channeled through data centers, and in some cases data should be published promptly. The data centers could provide a further service by providing information about data suitable for secondary use but not centrally archived, acting either as a "switching center" for requests or through the issuance of directories of data repositories as has been done for the Geodynamics Program. There are plans to take many new kinds of data related to the middle atmosphere and thermosphere that have potential multiple use and for which the archival and data retrieval problems remain to be worked out. It is noted that some work on this is being started by a Panel on Data Management for the international Middle Atmosphere Program (MAP). In this connection, NOAA is urged to strengthen its data activities in STP and in meteorology as regards providing data services in support of upper-atmosphere research; this will involve data types and data management problems that heretofore might have been regarded as unconventional. The NOAA data centers are urged to give more attention to compiling information about relevant data suitable for multiple use within the community and to providing suitable services to the community; a necessary corollary to this remark is encouragement to the scientists who generate such data to cooperate in this effort.

The intention of the SCOSTEP Steering Committee for MAP to develop a data management plan for that program that will result in a deeper consideration of many of the data problems is applauded.

The needs for the upper-atmosphere-research community for monitoring and data services of various types are now generally appreciated. The same appreciation seems to be visible in companion fields of solar-terrestrial research, magnetospheric physics, solar activity, and interplanetary physics. It is not effective to treat these problems of the needs for scientific services as peripheral to the assessments of research needs in each field separately; rather the subject should be considered as a whole. Thus a National Plan for the scientific services integral to or supportive of STP research should be developed.

6

THE ROLE OF GROUND-BASED REMOTE SENSING

Ground-based remote sensing has, and will continue to have, an important role to play in upper-atmospheric research. Whereas remote sensing from satellites is ideal for obtaining a global though intermittent view of the earth's atmosphere, ground-based remote sensing is more effective for making continuous observations and for intensive observations of phenomena of limited or small scale. We have considered the opportunities for ground-based remote sensing and make the following recommendations, without necessarily trying to assign any priorities among them.

6.1 SUBAURORAL INCOHERENT-SCATTER THERMOSPHERIC-WIND OBSERVATIONS

Pressure variations that establish thermospheric winds are created by solar EUV heating of the atmosphere and, at high latitudes, by energy deposition from particle precipitation and the auroral electrojet. Our present understanding of the average wind fields and their variations with day, season, and sunspot cycle is based on theoretical calculations that employ empirical models for the pressure variations (based on satellite data) and on experimental observations by means of incoherent-scatter and 630-nm airglow measurements. Thermospheric winds are quite variable because of fluctuations in the amount of heating taking place at high latitudes. The sudden onset of auroral heating deposits energy in the thermosphere that is transported to lower latitudes (and perhaps lower altitudes) via planetary, gravity, and acoustic waves.

While a polar-cap radar is needed to provide the capability of monitoring the energy input in the auroral zone at all local times, the study of the resulting wind fluctuations and the waves propagated toward lower latitudes requires a radar located south of the auroral oval with a scanning capability. *We recommend that an incoherent-scatter radar facility be established for the observation of thermosphere winds over a range of subauroral latitudes, provided that this can be accomplished within the next few years.* This could be accomplished relatively economically by placing a receiver and antenna well to the north of the Millstone Hill radar (in the vicinity of Roberval, Quebec) to permit operation in a bistatic mode (i.e., by viewing the ionosphere from two directions). It is possible that a suitable surplus antenna might be obtainable for this purpose. With this modification, the facility would measure N-S winds and electric fields simultaneously over a range of subauroral latitudes in which both are expected to vary considerably.

6.2 HIGH-LATITUDE MAGNETOSPHERIC/ATMOSPHERIC DYNAMICS OBSERVATORY

The existing incoherent-scatter radar facility at Chatanika, Alaska ($L = 5.6$), has proven to be an exceptionally valuable tool for studies of phenomena associated with portions of the auroral oval at night, the F-region trough, and the daytime plasmasphere. However, the facility is located too far south to monitor the auroral oval at all local times. The EISCAT facility being built in Scandinavia will be able to view the auroral oval over a longer interval of local time and provide observations that are needed to better understand the role of auroral processes in controlling the global circulation of the thermosphere and the behavior of the ionosphere. On the basis of present knowledge, it is clear the major scientific returns would accrue from the establishment of an incoherent-scatter radar facility at still higher magnetic latitudes near 76° to 78°.

Incoherent-scatter radar observations are critical for the measurement of the relatively intense heat input into the thermosphere believed to occur in the region of the midday auroral oval (the polar cusp and its "throat" region), which may be a major source of fluctuations in the thermospheric wind field. Such observations will also contribute significantly to the study of complex phenomena occurring at the poleward edge of the auroral oval, where direct linkage of magnetopause field-aligned currents takes place, and over the polar cap, where extensive neutral-gas acceleration and solar-proton precipitation occur and where there exists direct linkage to the interplanetary environment. An incoherent-scatter facility located near geomagnetic latitude 76-78° could probe these regions on a daily basis, providing direct measurements of ionospheric electric fields and currents, particle precipitation, lower-thermosphere winds, and Joule and particle heating rates. *It is recommended that various options for making incoherent-scatter radar observations at geomagnetic latitude Λ = 76-78° be explored and that an appropriate observatory be established at the earliest opportunity.*

6.3 MESOSPHERE-STRATOSPHERE-TROPOSPHERE AND STRATOSPHERE-TROPOSPHERE RADARS

High-power coherent VHF radars have the demonstrated capability of measuring winds and waves in the troposphere and stratosphere to 35-km altitude and in the mesosphere and lower thermosphere between 60 and 100 km. It is probable that they can be extended to measure motions at all altitudes between 1 and 100 km and the dynamical coupling that exists between levels. Such observations would be of special value in the investigation of the midlatitude stratosphere. *We recommend that efforts be made to exploit mesosphere-stratosphere-troposphere (MST) radar capability at midlatitudes.* An economical way of accomplishing this would be by upgrading an existing UHF radar, like that at Urbana, by adding additional antenna area.

In 1974, using the Jicamarca radar it was demonstrated that a powerful coherent radar is capable of measuring winds in the troposphere and lower stratosphere by measuring the Doppler shifts from echoes that are due to turbulent irregularities in the refractive index of the clean air. Additional measurements of this type have now been made at Chatanika (Alaska), Sunset Canyon (Colorado), Urbana (Illinois), the Max-Planck Institute in the Federal Republic of Germany, and Arecibo (Puerto Rico). The implementation of this technique is also planned at Millstone Hill (Massachusetts). Most of these radars do not provide data of this type at levels above radiosonde levels (about 30 km), but they do provide wind profiles with altitude continuously with a time resolution of minutes, vertical velocities with a precision of a few centimeters per second, and the opportunity to examine interrelationships between the wind profile and the intensity of turbulence. This technique will contribute significantly to the study of wave phenomena such as tides, gravity waves, and the instabilities that lead to turbulence. Possible future deployment of such stratosphere-troposphere (ST) radars may prove valuable in studying such phenomena as mountain waves and those circulations in clean air that lead to the formation of severe clear-air turbulence.

We recommend that the newly demonstrated capabilities of ST radars be exploited using existing radars in order to gain a fuller understanding of the importance of small-scale motions to the overall dynamics of the upper troposphere and lower stratosphere. Studies should be undertaken to examine the potential scientific return of a more extensive network of ST radars. Preliminary design studies of a transportable ST radar should be undertaken in order to establish the specifications and cost of an ST radar network.

6.4 APPLICATION OF NEW OPTICAL TECHNOLOGY TO UPPER-ATMOSPHERE STUDIES

Major advances in our knowledge of the chemically active minor species in the stratosphere have come about through the use of optical absorption techniques in observations made from the ground, as well as from balloons and aircraft. New techniques that greatly increase the spectral resolution and sensitivity of instruments in the visible and near-infrared regions have been developed. While airglow techniques are applicable only at night, it is now possible to make quantitative monochromatic all-sky observations of low-latitude airglow structures and relate them to the restricted sky coverage of incoherent-scatter measurements. At middle and high latitudes, digital maps of subauroral red (SAR) arcs and auroral structures can be produced by automated optical equipment. The rapid pulsations of auroral N_2^+ and atomic emissions can be determined to a time resolution of 0.02 sec by television imaging systems. Neutral and ion temperatures over limited height intervals of the mesosphere and thermosphere can be obtained with precision of about 10 percent and a time resolution of about 10 min. F-region neutral winds can also be determined to about 10 m sec^{-1} with a time resolution of 30 to 60 min, and further substantial improvements are likely. Wave motions in the mesosphere and thermosphere can be evaluated from oscillations in brightness of various features, as well as oscillations in rotational temperature of OH and $O_2(^1\Sigma)$.

Examples of such new optical techniques are multiple Fabry-Perot etalons; combined interferometric and spectrometric instruments; and the application of image orthicons, image intensifiers, and array detectors to existing instruments. The use of computers to control instrumental operation and permit on-line averaging of successive scans or inversion of interferograms further enhances the return.

The array detector is a technological development that is ripe for exploitation and application to optical instruments for the study of atmospheric chemistry, energetics, and dynamics. Such a device (which comes in a variety of specialized forms and shapes) is basically capable of recording simultaneously many spatial and/or spectral elements of an optical image. This property significantly increases the sensitivity of a system. The new detector is suitable for use with several instruments--interferometers for the measurement of neutral winds and temperatures, ion drifts and ion temperatures; all-sky imaging for studying the morphology and motion of airglow structures and auroral features; and energy input by particle precipitation. In concert with an incoherent-scatter radar, a high-resolution, high-sensitivity interferometer provides a powerful technique for long-term measurements of atmospheric chemistry, energetics, and dynamics.

We recommend that advances in optical technology recently developed for use on spacecraft be exploited by further development and upgrading of instrumentation for ground-based studies of the energy sources, chemistry, and dynamics of the upper atmosphere.

6.5 METEOR-WIND RADAR

In the meteor-wind radar technique, a high-frequency (HF) radar signal is transmitted from the ground, reflected from a meteor ionization trail, and then detected at the ground. Winds acting on the trail cause a Doppler frequency shift to be seen in the returned signal. Thus one can measure the line-of-sight velocity component. Since ionization trails typically extend over an altitude range of about 75-105 km, the meteor radar can measure winds over that altitude range.

One may identify two basic classes of meteor-wind radars. One uses a relatively low transmitted power (on the order of tens of kilowatts in a pulsed mode), while the other uses transmitted power more than an order of magnitude greater. The former class may be operated continuously without great expense and can determine tides and prevailing winds averaged over several days. The latter type is more expensive to operate but can be used to study day-to-day variability of motions as well as gravity waves.

The meteor-wind radar technique is the *only* ground-based technique that is capable of obtaining winds continuously over a 24-hour period in its applicable altitude range. Also, an international coordinating organization has existed now for some years and has already performed some network studies of dynamics in the region of the mesopause.

We recommend that present meteor-wind radar studies be continued and that efforts be made to coordinate them with an emphasis on determining prevailing wind fields. We also recommend that consideration be given to including meteor-wind radar capability in newly constructed ST and MST radars. In this connection, we believe that it would be most valuable to operate a meteor-wind radar at Jicamarca, where a proven MST capability exists at a unique tropical location and where the lower thermospheric extension of mountain waves can be studied.

6.6 AIRGLOW MEASUREMENTS OF F-REGION WINDS

Interferometric observations of the Doppler shift of the oxygen red line (630 nm) provide the only ground-based technique for the direct determination of nighttime F-region neutral winds. Incoherent-scatter radars provide the ion-drift velocity from which meridional winds can be derived, together with the variation of the neutral temperature from which some information on the zonal wind can be inferred. The optical measurements have a demonstrated capability for the measurement of nighttime winds with a precision of about 10 m sec^{-1} and a time resolution of 30 to 60 min under the low-signal conditions that exist outside auroras, and new image-plane detector technology should lead to substantial increases in precision or in time resolution in the near future. For bright auroral emissions, the capabilities of the technique are greater.

We recommend that red-line interferometers be operated in conjunction with incoherent-scatter radars in studies of F-region dynamics.

6.7 PARTIAL REFLECTION DRIFTS AND LIDARS

Two new techniques offer the possibility of measuring the velocity field in the mesosphere and lower thermosphere at reasonable cost, namely, sodium lidar velocimetry (nighttime) and partial-reflection drifts (daytime). *We recommend that sodium lidar and partial-reflection techniques be further studied and developed to determine their usefulness compared with MST and meteor-wind radars for determining mesospheric winds.*

6.8 PLASMA IRREGULARITY AND INSTABILITY STUDIES

Radar observations of plasma instabilities and irregularities have been fruitful and should be continued and expanded. Sufficient progress has been made in the experimental and theoretical studies of plasma instabilities and irregularities that intensive campaign-type operations involving rockets, radar, scintillation detectors, and other ground-based instruments hold great promise of increasing understanding of the nonlinear evolution of these processes. Since natural plasma-instability processes operate in the saturated nonlinear regime, understanding them is essential in order to gauge the anomalous transport effects of such phenomena. Furthermore, these studies will allow detailed testing of the computational model that is the major realistic theoretical method available for study of large-scale partially ionized systems. Examples of important studies of this type are an equatorial electrojet and spread-F campaign at Jicamarca, a campaign to study the artificially produced plasma waves and irregularities in heating experiments at Arecibo and possible high-latitude sites, and a study of irregularities generated at high latitudes. In addition to the plasma-physics interest and the testing of computational models, each of these phenomena has importance in understanding the irregular structure observed in the ionospheric plasma on scales from fractions of a meter to tens of kilometers. These irregularities severely affect propagation in VHF and even SHF communication systems.

We recommend that radar studies of natural and artificially generated irregularities and instabilities in the ionosphere continue to be supported. These studies should be supplemented by sounding-rocket measurements as well as relevant ground-based techniques.

6.9 ACTIVE EXPERIMENTS

Active experiments in space allow the cause-and-effect methods of laboratory experimental physics to be applied to large-scale systems. The HF heating experiments at Platteville, Colorado, and Arecibo, Puerto Rico, have produced fruitful results for both aeronomy and plasma physics. The first detailed observations of parametric instabilities were made with high-power radio-wave injections, and a wealth of effects remains to be explained theoretically. Active experiments involving VLF wave injection into the magnetosphere are being used to investigate energetic particle dumping into the atmosphere. Chemical releases from rockets have been used to stimulate large-scale plasma instabilities and to study thermospheric chemistry. These will continue and will be expanded in the Space Shuttle era. During the Spacelab II flight, water vapor will be injected over the Arecibo, Jicamarca, and Millstone Hill radar observatories, as well as the Roberval VLF receiving station. Electron beams will be used extensively from rockets and the Space Shuttle in the coming years; these experiments depend to a large degree on ground-based observations for their interpretation. Rocket probing of perturbed regions has occurred and in some cases will be necessary in future experiments. A feasibility study should be made of launching rockets into the region heated from Arecibo carrying instruments such as Langmuir probes and ion-acoustic wave detectors. Other important ground instruments that have been used include scintillation detectors, coherent as well as incoherent-scatter radars, digital ionosondes, and optical instruments.

We recommend that active experiments be supported to apply the cause-and-effect approach to the study of upper-atmospheric phenomena. Examples of experiments to produce an effect are the HF heating experiments, VLF stimulation of the magnetosphere, electron-beam experiments, and chemical releases from rockets and the Space Shuttle. Examples of essential instruments to study the effects include coherent- and incoherent-scatter radars, optical instruments, and rocket probes.

6.10 DYNAMICAL STUDIES OF THE MIDDLE ATMOSPHERE AT JICAMARCA

The Jicamarca Radio Observatory was established with U.S. funds to study the equatorial ionosphere. It is also the

VHF facility where the mesosphere-stratosphere-troposphere (MST) radar capability was first developed. Many groups in the world are proposing, building, or planning to build MST radars at various locations. Jicamarca has a proven MST capability, a unique tropical location, and the ability to study the upward propagation of mountain waves. *We recommend that Jicamarca be supported sufficiently to exploit its unique capability for dynamical studies of the middle atmosphere.*

6.11 MEASUREMENT OF TRACE CONSTITUENTS BY HIGH-RESOLUTION SPECTROSCOPY

Ground-based millimeter-wavelength spectroscopic observations have been used to determine the total column densities and the crude altitude profiles of O_3, CO, and H_2O in the stratosphere and mesosphere. The extension of high-resolution spectroscopy to infrared and optical wavelengths where the line strengths are large, and to well mixed species like O_2, makes it possible to measure other species and to deduce temperature profiles and velocities. *We recommend the continuing development of high-resolution spectroscopy for the measurement of trace constituents and physical conditions in the stratosphere and mesosphere.* In particular, we recommend practical demonstrations of these techniques by measurement programs to produce both scientific data and estimates of their real performance, limitations, and cost.

6.12 IMPROVED OZONE TOTAL-COLUMN MEASUREMENTS

The most important ultimate test of our understanding of the effects of natural and man-made changes in atmospheric ozone will be provided by monitoring the long-term changes. We now have long-term data from the Dobson network, but it is clear from the intercomparisons between Dobson data and the BUV data from satellites that the Dobson data are not so accurate as desired or as previously thought. There are several possible ways of improving the precision of the ground-based total-ozone measurements. The new microwave measurements of ozone and improved UV techniques that use an automated fit to the full spectrum in the near ultraviolet offer the possibility of ozone total-column measurements to a precision of a few tenths of a percent. *We recommend that studies be made of new microwave and UV techniques for* *ground-based measurement of total ozone with eventual testing of at least one of these instruments, including comparison with a Dobson instrument.*

6.13 AIRGLOW DETERMINATION OF O_3, H, AND O DISTRIBUTIONS

Important mesospheric chemical species such as O_3, H, and O can be effectively studied by observations of metastable emissions in the nightglow that arise from luminescent reactions involving them. Such observations can be made from the ground over a considerable solid angle enclosing some hundreds of kilometers horizontally. *We recommend that airglow observations be exploited as an effective method of determining the distributions of O_3, O, and H.*

6.14 AIRGLOW STUDIES OF THERMOSPHERIC AND EXOSPHERIC PROCESSES

Ground-based airglow observations provide useful information on temporal variations of thermospheric composition. Examples are the study of changes in the O/N_2 and O/O_2 ratios from auroral and twilight investigations of $O(^1D)$ emission at 630 nm. A subtle interplay between direct observation, modeling, and laboratory measurements is involved, but the inferences can be made rather clearly. In the case of twilight photometry, for example, one finds a geomagnetic dependence of the O/N_2 ratio in the thermosphere whose origin must lie in the modification of vertical transport rates near the homopause. Even the profile of atomic oxygen can be monitored (under quiet conditions) as high as 500 km using twilight photometry of the emission from $O^+(^2P)$ at 732 nm. The effects of lower-thermospheric heating on composition (the O/N_2 ratio) can be studied where auroral photometry is combined with incoherent-backscatter measurements--an example of the usefulness of coordinated measurements.

Optical observations make a unique contribution to studies of thermospheric photochemistry by providing the only direct information on the densities of chemically active metastable species and by providing the integrated rates at which particular photochemical reactions occur. Especially important is the information that can be obtained by optical means on the rates of production of ionization both by energetic particle bombardment and by solar EUV radiation. Optical measurements of the atmosphere also provide information that is hard to obtain in laboratories on some basic atomic and molecular parameters and reaction mechanisms.

As the exosphere is approached, the importance of ground-based photometry is maintained through studies of twilight helium emission and the geocoronal hydrogen glow. These studies have provided and will continue to provide basic information on the outermost layer of the atmosphere, where large-scale transport dominates the picture.

We recommend that airglow observations be exploited to determine the role of metastable species in thermospheric photochemistry and the distribution of helium and hydrogen in the exosphere.

6.15 ARCHIVING OF INFRARED SOLAR SPECTRA OBTAINED WITHIN THE ATMOSPHERE

A number of molecular species are being added to the troposphere as a result of man's activities. The possibility exists that some of them may become a possible threat to the ozone layer or otherwise detrimentally affect the upper atmosphere. The question of whether such molecules will be important in the chemistry of the ozone layer depends among other things on their tropospheric lifetimes. The accuracy of the estimates of the tropospheric lifetime of a molecule can be significantly increased if data are available concerning its tropospheric concentration at earlier times. Infrared solar spectra obtained from the ground at high-altitude "dry" sites or from balloons contain many features that have not been identified. Many of these are undoubtedly due to weak lines of such common constituents as CH_4, O_3, and H_2O. However, a significant number are due to as yet unidentified molecules, including pollutants. The number and strength of such features will change with time, and the corresponding variations in concentration, especially secular trends, are important. *It is recommended that a program of obtaining and archiving infrared solar spectra obtained within the atmosphere on a routine basis (several times a year) be started for the purpose of monitoring total atmospheric content of minor constituents.*

6.16 DATA MANAGEMENT FOR STRATOSPHERE CHEMISTRY AND AEROSOLS

Observational programs involving surveys and repetitive measurements will produce data sets that should be available for intercomparison and reinterpretation at later times. In order to assure preservation of and accessibility of such data, *it is recommended that NOAA carry out the necessary data-management functions to keep track of what data exist on stratospheric composition and where they are archived. It is further recommended that funding agencies for stratospheric chemical research prescribe that investigators maintain suitable documentation of data sets and cooperate with NOAA data management and services.*

6.17 CLUSTERING OF OBSERVATION FACILITIES

Coincident and complementary measurements of various parameters characterizing the state of the atmosphere that utilize the unique capabilities of various measurement techniques enhance the value of each individual measurement. *We recommend that, where practicable, major installations such as an incoherent-scatter radar be augmented with a cluster of facilities such as sounding-rocket and balloon launch sites, passive and active optical observatories, and other electromagnetic sounding systems.*

7

THE ROLE OF *IN SITU* MEASUREMENTS FROM AIRCRAFT, BALLOONS, AND ROCKETS

In situ measurements from aircraft, balloons, and sounding rockets are essential to the investigation of the upper atmosphere, and they will remain so regardless of the development of improved remote sensing from the ground and from satellites. The types of *in situ* measurements that cannot be replaced by remote sensing include many measurements of concentrations of minor constituents, the determination of vertical profiles of quantities that cannot be remotely sensed from satellites or from the ground, and the investigation of some small-scale phenomena. In some cases, *in situ* measurements will be required to establish the validity of remote-sensing techniques. Thus, even with the optimum development of satellite and ground-based remote-sensing techniques, it is essential that a strong capability for *in situ* measurements from aircraft, balloons, and rockets be preserved. In a few important cases it will also be valuable to employ remote-sensing techniques from these platforms, for example, lidar in aircraft and spectrographs or photometers in balloons or rockets. And once again, it is worth emphasizing that the coordination of such observations with remote sensing from the ground or from satellites, will lead to more nearly complete results than can be obtained from the same observations made sporadically and independently.

7.1 SOUNDING ROCKETS AND BALLOONS AND THEIR LAUNCH SITES

Sounding rockets and balloons provide the only means of yielding verticle profiles of atmospheric properties by direct probing in the altitude range from about 20 to 135 km. *In situ* sampling will continue to be necessary to complement remote sensing from satellite platforms during the 1980's. Sounding rockets and balloons provide the only means of observing some phenomena and measuring many atmospheric species over certain ranges of altitudes. Rockets also allow for measurements on spatial scales inaccessible to satellites. For example, in plasma instability studies the small-scale structures are difficult to measure on rapidly moving spacecraft. In addition, rockets can be held in readiness for long periods of time waiting for the correct geophysical conditions. Sounding-rocket measurements must be made at many latitudes and times.

We recommend that the balloon and sounding-rocket program be preserved during the Space Shuttle era to make important atmospheric measurements that cannot be made from satellites. We further recommend the maintenance and, where required, the expansion of rocket and balloon launch facilities to accommodate the needs for data acquisition at various geographical locations. Provision should be made for fixed sites as well for remote campaigns.

7.2 STRATOSPHERIC AND MESOSPHERIC COMPOSITION AND PHOTOCHEMISTRY

A promising start has been made during the past few years on the study of the chemistry and large-scale quasi-horizontal transport processes in the stratosphere. In large measure this work has served to expose our ignorance of this important and neglected region of the atmosphere, the one most closely coupled to the lowest portion in which we live. *We recommend that the momentum now established in stratospheric investigations be vigorously maintained. To do this we need to exploit present methods of both* in situ *and remote sensing of chemically active minor constituents and to develop new methods. We also strongly encourage study and development of methods, particularly those using tracers, for examining the global-scale horizontal movement of air masses within the stratosphere.*

Knowledge of the concentration of minor species in the mesosphere is limited. The photochemistry of this region should be relatively simple. Yet the few measurements of such mesospheric species as OH and NO that exist and some for O_3 are in strong disagreement with theoretical predictions. It is important that the photochemistry and composition of the mesosphere be understood if we are to hope to understand more complex regions. *We recommend that a program be undertaken to determine the distribution of mesospheric constituents. Relevant photolysis rates should* *also be measured*. Instruments carried on parachutes dropped from sounding rockets in the neighborhood of 90 km may provide improved measurements of species such as O, O_3, OH, HO_2, and NO.

7.3 STRATOSPHERIC-TROPOSPHERIC EXCHANGE

While vertical exchange processes are fast in the troposphere, they are on the average slow in the lower stratosphere. The rate of transfer to the stratosphere of water vapor and many natural and man-made gases that are inert in the troposphere is determined by dynamical exchange between these regions of the atmosphere. Under the action of ultraviolet radiation, these gases are broken down at higher levels into highly reactive radicals that affect the photochemistry and heating of the upper atmosphere. The residence time and integrated photochemical activity of these radicals is determined by dynamical exchange processes between the stratosphere and troposphere. These exchange processes, the composition of the air being exchanged, and interhemispheric differences are not well known at present. *We recommend that more observational and theoretical studies be devoted to the stratosphere-troposphere interchange processes and that fast-response instrumentation be developed for measurements of chemical constituents (e.g.,* O_3*,* H_2O*, CO) in support of these studies*. The combinations of these measurements can only be made employing *in situ* instrumentation or aircraftborne lidar. Some support may also be provided by ground-based radar observations.

7.4 PLANETARY ELECTRODYNAMICS

Electric fields are present at all height levels of the atmosphere and have a significant impact on the energy budget in the thermosphere. Magnetospheric fields are most important at high latitudes, where they are driven by the solar-wind interaction with the earth's magnetic field. The strength in the thermosphere is sufficiently large to cause momentum transfer between the plasma and the neutral atmosphere. This driving force and the pressure gradient force due to particle heating modify the wind patterns. High-altitude electric fields have been shown to penetrate to stratospheric levels and perturb the global atmospheric electric potential. This mapping of electric fields is one of the few clear, almost instanteous coupling mechanisms between upper- and lower-atmospheric processes. Quantitative modeling of the upward mapping of fair weather and thunderstorm-related electric fields has recently begun. With the possible exception of mesospheric electric fields, measurement techniques are well developed, and a unified model of planetary electrodynamics should be a goal of the 1980's. Examples of outstanding problems in planetary electrodynamics include mesospheric and stratospheric electric fields, upward mapping of tropospheric fair-weather and thunderstorm fields, and polarization electric fields in the electrojets; polar-cap, polar-cusp and auroral-zone electric fields and their penetration to lower latitudes and altitudes are further examples. *We recommend investigation of atmospheric electric fields of magnetospheric, ionospheric dynamo, and thunderstorm origin to determine their role in mesospheric transport and chemical processes.* The investigation should use theoretical and experimental approaches including ground-based, balloon, and rocket measurements. Balloon platforms are an attractive way to study in a coordinated way the parameters associated with observed perturbations in the middle-atmosphere electric field due to precipitation events, thunderstorms, and conductivity variations. Payloads should measure quantities such as the vector electric field; x-ray, ion, and electron fluxes; and conductivity. NASA should be urged to support the study of mesospheric electrodynamics with rockets.

The electrodynamics payloads for balloons and rockets will address the problem of mesosphere and stratospheric conductivity enhancements and their influence on the fair-weather electric field at high latitudes. Such measurements will yield a data base for understanding the global impact of electrical perturbations and their possible role in sun-weather physics. In addition to these middle-atmospheric processes, these payloads will measure horizontal electric fields of magnetospheric origin in the polar cap and auroral oval. Flown in the southern hemisphere, the payloads would complement the extensive northern hemisphere measurements made by incoherent-scatter radar and the magnetospheric-physics investigations being conducted in the Antarctic regions.

Incoherent-scatter radar is a powerful tool for measuring quasi-static electric fields above 100-km altitude and should be encouraged at existing observatories; increased capability for sensing at subauroral latitudes was recommended earlier, and the desirability of polar-cap and polar-cusp measurements was also indicated. Since such facilities can also measure electron density, the Joule and particle precipitation heating can be evaluated.

Event-type measurements of auroral microstructure and generation of strong neutral winds in auroral events requires rocket investigations, which implies a need for an auroral-zone rocket range (e.g., Poker Flat) and a healthy sounding-rocket program.

7.5 MESOSPHERIC ION COMPOSITION

Critical gaps still exist in the understanding of the processes controlling the formation of mesospheric ions, the recombination processes, and in some cases the ion composition itself, particularly negative ions. *We recommend that measurements of mesospheric ion composition be carried out under a variety of conditions, with particular emphasis on alleviating the paucity of meaningful data on negative ions.* The measurements require the use of sounding rockets both directly and for the deployment of parachuteborne packages. It is visualized that the primary instruments will be mass spectrometers supplemented by measurements of other parameters such as conductivity, mobility, and electron concentration.

7.6 CHEMISTRY IN THE LOWER THERMOSPHERE

The region from 80 to 135 km remains one in which our knowledge of atmospheric composition and structure is meager. A determination of the densities of species and understanding of the transport processes involved in this region are crucial for the understanding of a number of aeronomic problems. Examples are the distributions of the oxygen allotropes, metals, and metal ions and the molecules and radicals (H_2O, CH_4, H_2, OH, HO_2, and H) involved in the generation of atomic hydrogen required to supply the hydrogen escape flux. *We recommend that efforts to develop methods to determine the distribution of atmospheric species in the lower thermosphere and to understand transport processes in the 80- to 135-km range be encouraged.*

7.7 MESOSPHERE AND LOWER-THERMOSPHERE DISTURBANCES

It is important to study disturbances in the lower ionosphere both because they are associated with practical effects, such as those affecting radio communications, and because we wish to understand these geophysical events themselves and their effects on the atmosphere. Although isolated measurements of one or a few parameters are interesting, understanding will likely be much further advanced by a concerted coordinated measurement program characterizing the energy input to the atmosphere and the resulting perturbations of composition, ionization, and excitation/emission.

In situ measurements of the perturbations and the distributions of charged and neutral atmospheric species, coupled with measurements of IR, visible, and UV emissions by ground-based and rocketborne instruments, are important in the light of data on the energy-input mechanisms as determined grossly from the ground and detailed by rocketborne instruments. The important geophysical events to be considered include (a) different types of auroral and other particle precipitation events such as polar-cap absorption events and (b) lower-latitude events such as magnetic-storm effects and the D-region winter anomaly. These events will be more important and more easily observed in the ensuing years of increased solar activity.

Much can be learned about atmospheric processes and atmospheric disturbances by coordinated measurements of the input-output type utilizing events such as auroras, solar proton events, and planetary-wave-induced anomalies as stimuli. *It is recommended that continued emphasis be given to measurements of energy inputs and other causative phenomena and the resulting effects on ionization, excitation radiation, chemical composition, and heating*. A coordinated program of *in situ* rocket measurements coupled with measurements from ground-based instruments will be required.

7.8 MAINTENANCE OF THE METEOROLOGICAL ROCKET NETWORK

The meteorological rocket network is identified as an essential tool for certain tasks such as the calibration and extension of satellite data and the measurement of temperature profiles during times of winter disturbances. *We recommend that the existing meteorological rocket network be maintained, at least until such time as alternative measurement systems have been established and adequately tested, to ensure the continuity of high-quality data.*

7.9 SOURCES OF IMPORTANT STRATOSPHERIC REACTANTS AND INFRARED ACTIVE GASES

Stratospheric ozone-layer photochemistry is strongly controlled by reactions involving highly reactive chemicals, especially radicals, that are present in small concentrations ($1:10^{12}$ to $1:10^{8}$) and that act catalytically. These radicals of the nitrogen oxide, hydrogen oxide, and chlorine oxide families are produced by photochemical reactions in the upper atmosphere from H_2O and other *source* molecules (e.g., CH_4, N_2O, CH_3Cl, CH_3CCl_3) that are released at ground level largely by biospheric or industrial processes and that are relatively inert in the troposphere. In many cases the strengths and even the identities and locations of the dominant ground-level sources are not known. Identical remarks apply to some of the sources of the stratospheric sulfate aerosol (e.g., COS), for other halogenated species, and possibly for metal compounds. Similarly, the atmospheric sinks of these source molecules, other than reactions with OH, excited oxygen atoms, and ultraviolet photons, are not known quantitatively. *We recommend both exploratory measurements to locate and quantify sources and sinks in the troposphere of stable source molecules that give rise to highly reactive radicals in the stratosphere and regular monitoring of their tropospheric abundances with adequate frequency and coverage in both hemispheres.*

We also note that reaction with OH in the troposphere is the main atmospheric sink for many important trace gases that reach the stratosphere (e.g., CH_4, CH_3, Cl, CH_3, and CCl_3). The tropospheric OH concentrations are determined primarily by the tropospheric distribution of ozone, so that the origin of tropospheric ozone must be known (stratospheric origin versus *in situ* tropospheric production). *To deduce whether tropospheric O_3 is primarily of stratospheric or of tropospheric origin, we recommend an expanded program of airborne and surface measurements of tropospheric O_3, especially in the southern hemisphere.*

In the stratosphere many trace gases are further broken down by photochemical processes, and their vertical, latitudinal, and seasonal distributions are a useful tool to clarify stratospheric photochemistry and transport processes. At levels above about 30 km, the average odd-oxygen and the odd-hydrogen concentrations are determined by photochemical reactions. Especially in the lower stratosphere, chemical interactions give rise to such molecules as $HONO_2$, HO_2, NO_2, HOCl, and $ClONO_2$, which do not react with ozone, so ozone at its level of maximum concentration is protected from otherwise larger photochemical destruction. *We recommend that simultaneous airborne measurements be made of lower-stratospheric radicals and their recombination products including O_3, O, OH, HO_2, NO, NO_2, Cl, ClO, $ClONO_2$, $HONO_2$, HO_2, NO_2, HOCl, and HCl, along with temperature and relevant photodissociation rates, to test the completeness of schemes of stratospheric photochemistry in those regions where concentrations are mainly determined by photochemical processes.*

Possible temporal trends in these stable source-molecule concentrations must be identified, not only because of possible stratospheric impact but also because of their ability to trap outgoing planetary radiation. For these tropospheric measurements, methods such as whole-air sampling, infrared spectrometers, mass spectrometers, and gas chromatographs can be employed at ground locations or on aircraft and small balloons.

It must also be emphasized that stratospheric ozone concentrations have importance beyond their contribution to the total ozone column and the UV shield. Stratospheric thermal structure and dynamical circulation patterns are strongly controlled by the heat input due to UV absorption by O_3 above 30-km altitude and by cooling from the 9.6-μm-band of O_3. Surface climate might be influenced by these O_3 radiative processes.

7.10 MEASUREMENT OF STRATOSPHERIC AEROSOLS

The concentration of a worldwide layer of stratospheric aerosols is greatly enhanced after major volcanic eruptions, with maximum concentrations occurring at about 20 km. Following such events, a significant warming of the stratosphere has been observed, and records of global average temperatures suggest a surface cooling persisting for several years. In order to understand the relationship between stratospheric aerosols and such climatic effects, their ability to absorb and scatter radiation must be known.

Recent studies indicate that appreciable aerosol mixing ratios exist at altitudes much higher than the layer of maximum concentration. The chemical composition of stratospheric aerosols has been reported to be variable; sometimes they exist primarily as sulfuric acid and sometimes as ammonium sulfate. Since composition significantly affects the optical properties of the aerosol, it should be continually measured and efforts made to understand the causes of such variability. The formation mechanism of stratospheric aerosols is still not understood. During periods of no volcanic injections above the tropopause, it is believed that diffusion of tropospheric sulfur-containing gases into the stratosphere provides the substance for aerosol formation. The vertical distribution of such gases as water vapor, carbonyl sulfide, and sulfur dioxide should be determined. It has also been postulated that sulfuric acid aerosols evaporate above 30 km, giving rise to sulfuric acid vapor. The existence of this vapor could be confirmed experimentally.

We recommend that the properties of stratospheric aerosol particles that control their interaction with visible and infrared radiation (e.g., the size distribution, shape, and complex refractive index) be measured with instrumentation on high-altitude aircraft and balloons to provide a more accurate assessment of the effect of the particles on the energy budget of the atmosphere and on gas concentrations and temperature profiles. We also recommend that the formation of stratospheric aerosol particles be studied by using in situ *data on aerosol chemical composition, condensation nuclei, and gaseous aerosol precursors (e.g.,* H_2O, *COS,* SO_2, *and possibly* H_2SO_4 *vapor).*

7.11 MEASUREMENT OF DIRECT AND SCATTERED SOLAR ULTRAVIOLET RADIATION WITHIN THE UPPER ATMOSPHERE

The atmospheric absorption spectrum in the ultraviolet and the structure of the solar spectrum make it difficult to calculate satisfactorily the penetration of solar ultraviolet radiation into the atmosphere, and, as a consequence, the altitude profile of rates at which various photoprocesses proceed cannot be determined with the desired precision. This presents a serious limitation in many studies of photochemistry of the upper atmosphere. *We recommend that observations of the direct and diffuse solar ultraviolet spectrum be made as a function of altitude using instrumentation on balloons and rockets for validation and improvement of calculations of chemical photodissociation rates and rates of energy deposition in the upper atmosphere.*