RADIATION IN THE ATMOSPHERE

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FOREWORD

The Radiation Symposium held in Garmisch-Partenkirchen, FRG, 19-28 August 1976 was organized jointly by the Commission on Atmospheric Chemistry and Global Pollution, and the Radiation Commission of the International Association of Meteorology and Atmospheric Physics. It succeeded in bringing together atmospheric physicists and chemists concerned with formation and dynamics of aerosol and cloud particles and those working in the field of atmospheric radiation. The participation of nearly 300 scientists representing 32 nations reflected the growing interest in the interaction between atmospheric composition and radiative transfer in the atmosphere.

Major progress has been achieved during the last few years in understanding the formation and growth of particles in the atmosphere, in determining their optical properties, and in computing of radiative fluxes in clouds and in polluted atmospheres. In the context of research on climate and its possible variations, however, new problems have surfaced. It has become apparent that more precise information is required than has hitherto been available on the problem of energy transfer in real atmospheres. Thus, the effects of broken cloud fields in addition to the effects of aerosols inbedded in the clouds need to be modelled in radiation/climate calculation. Significant results of this difficult task were discussed at the conference. Moreover, satellite and ground-based remote sensing techniques were developed to such a degree that the stage is set for large scale observations of the atmospheric parameters that are expected to have an impact on climate or are possible indicators of climate changes. Pilot studies in this direction, which were undertaken during GATE, were reported at the Symposium and plans for future global monitoring were described.

The results of the Symposium are published in these Proceedings in the form of extended abstracts of the papers presented at the Symposium. These papers are reproduced as they were submitted by the authors.

The Symposium at Garmisch-Partenkirchen was organized in collaboration with and partially supported by a number of international scientific organizations. We would like to express our appreciation to the following for their financial support and co-sponsorship of the Symposium:

American Meteorological Society (AMS)
Committee on Space Research (COSPAR)
International Union of Geodesy and Geophysics (IUGG)
World Meteorological Organization (WMO)

In addition, we wish to record our sincere appreciation to the national organizations that also co-sponsored the Symposium and whose generous financial support represented a major contribution to its success:

Bayerisches Staatministerium für Unterricht and Kultus
Deutsche Forschungsgemeinschaft
Deutsche Meteorologische Gesellschaft e. V.
Deutsche Wetterdienst
Kurwerwaltung Garmisch-Partenkirchen

I would also like to thank my colleagues on the Scientific Program Committee and the Local Organizing Committee whose names are listed in the back of these Proceedings.

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President, Radiation Commission

Observations of the Solar Flux at the Top of the Atmosphere -- A Brief Overview

From the time when they were first set up, both the Commission for Radiation and Insolation of the IMO (now the WMO) in 1896, and the Radiation Commission of IUGG in 1924, were concerned with determination of the solar constant and the spectral distribution of the solar irradiance at the top of the atmosphere. The problems involving solar radiation which were of primary concern during those early days were:

1) Development of suitable instruments and the establishment of a surface network for observations of solar radiation;
2) Determination of the equivalence of observations derived from the various "semi-standard" instruments in use and being developed during that time. This led ultimately to the establishment of the International Pyrheliometric Scale (IPS) in 1956; [After 20 years of use of the IPS of 1956, the atmospheric radiation community has finally recommended adoption of coherence to the international system of units (SI) in application to absolute radiometry, thus resolving a long standing problem in reporting radiation measurements.]
3) Development of a program of measurements of the solar constant and its possible variations;
4) Measurements of the near ultraviolet solar radiation, particularly in the region of the ozone cut-off and observations of total ozone in the atmosphere.

Although a great deal of progress has been made during the past fifty years toward resolving these problems, there is, as I will indicate in the following remarks, much still to be done.

In the period before 1930, all observations of solar radiation were made from ground-based stations, generally located at high mountain observatories. Measurements were extrapolated to zero air mass to give values of the solar irradiance at wavelengths down to the atmospheric ozone cut-off at about 2950Å (e.g. Pettit, 1932). Although the lower spectral limit was extended slightly during the 1930's when a few individual observations of the solar irradiance were obtained from free air balloons flying at heights of about 30 km (see, for instance, Mitra, 1948), it was not until October 1946 that instrumented rockets were able to penetrate the ozone layer to give the first space observations of the solar ultraviolet spectrum down to about 2200Å (Baum et al., 1946). Eleven years later, in October 1957, a new chapter was started in the development of platforms for terrestrial and space observations in general, and observations of solar irradiation in particular, with the launching of Sputnik I. Satellites represent the best platforms available today for determining the total solar irradiance (and its spectral distribution) at the top of the atmosphere and for monitoring their variations.

Both solar and atmospheric physicists are concerned with solar radiation studies. These interests, however, stem from two somewhat different, but complementary points of view. The solar physicist needs to measure the solar flux at all wavelengths, from X-ray to radio with high spectral, spatial and in many cases, temporal resolution. This information contributes to a basic understanding of the structure and the dynamics of the sun and other stellar systems. On the other hand, the atmospheric physicist, who is concerned primarily with the region of the atmosphere below 100 km, needs to know the solar irradiance in the spectral interval involved in determination of the atmospheric chemical and thermal structure and which provides energy input for driving the atmospheric-ocean circulation system.

It is the custom among some observational solar physicists to determine the solar radiance by making high resolution spectral measurements of the solar intensity at the center of the solar disk and extrapolating these measurements to the entire disk by correcting them for limb darkening (or limb brightening). This involves quasi-empirical extrapolation in two different modes -- one for the solar continuum and the other for the numerous absorption and emission lines of the solar spectrum. To the extent that there are significant differences in the structure of the sun in equatorial and polar sections, the assumption of universally applicable limb darkening corrections, normally used to derive the whole disk solar flux, is inherently inaccurate. Where spatial variations of the emitted solar flux over the solar disk are relatively small in the near ultraviolet, visible and near infrared spectral regions, whole-disk observations are generally preferred.

Observations of the solar constant are, of course, of intrinsic interest to meteorologists, since the brightness temperature of the planet and its overall climate depends on the value and possible variations of the solar constant. However, the earth's atmosphere is not a gray absorber. Therefore, accurate values of the spectral distribution of solar irradiance are needed in order to calculate the absorption by gases, clouds and aerosols in the atmosphere and to calibrate, through use of space observations, the spectral variations of the earth-atmosphere albedo. Note that only about 10^{-2} percent of the total solar irradiance (solar constant) is contained in the spectral interval shortward of 2100Å, about 1% shortward of 3000Å; about 50% shortward of 7300Å and 99% shortward of 4μm. Thus about 50 percent of the solar energy is in the spectral region where atmospheric gases (primarily H_2O and CO_2) play an important role in the absorption of solar energy in the lower 90 percent of the earth's atmosphere.

Solar radiation in the spectral region beyond 1500Å is primarily a continuum superimposed by numerous absorption and/or emission lines. The continuum in the visible and infrared originates in the photosphere and is due to negatively ionized hydrogen. In the ultraviolet the continuum has its origin in the upper photosphere and lower chromosphere and is most closely associated with the ionization limits of various metallic atoms. At wavelengths shorter than about 1μm there is an increasing number of Fraunhofer (absorption) lines in the solar spectrum. At 5000Å approximately 10 percent of the continuum radiation is reabsorbed by these lines and at 3000Å this absorption increases to about 50 percent. This high percentage of absorption continues to about 2100Å. At 2100Å the continuum shows an abrupt decrease associated with the ionization limit of neutral aluminum. At shorter wavelengths the radiation continuum has its origin at a level in the solar atmosphere close to the temperature minimum and most of the lines below about 1850Å appear in emission. The brightness temperature of the solar continuum is a minimum of $T_B \approx 4500$ at $\lambda \approx 1500$Å.

The ultraviolet solar spectrum is of particular importance in determining the composition, temperature distribution and circulation patterns of the stratosphere, mesosphere and thermosphere. The strongest emission line in the UV is Lyman-α (1216Å) due to neutral hydrogen. The energy contained in the solar Lyman-α flux is as large as the total solar flux in the continuum and other lines in the spectral interval from 1000 to about 1750Å. Because Lyman-α occurs at a spectral window of molecular oxygen, solar radiation at this wavelength can penetrate down to about 60 km in the earth's atmosphere. At these levels water vapor can be photolyzed by solar photons, thus significantly affecting the photochemistry in the upper mesosphere.

Solar radiation at wavelengths between about 1750 to 2100Å results in dissociation of molecular oxygen and the subsequent production of ozone in the stratosphere and mesosphere. At longer wavelengths (2100 to 3100Å) solar energy is absorbed by stratospheric ozone producing the positive temperature gradient in the stratosphere and the temperature maximum at the stratopause. Recent awareness of the complexity of stratospheric ozone photochemistry has resulted in an increased focus of attention to the need for accurate measurements of the solar irradiance in the range 1800 to 3100Å.

The observed distribution of solar irradiance at the top of the atmosphere in the spectral interval 1500 to 3000Å is given in Fig. 1. The curve shown in Fig. 1 represents an average based on data recently compiled by Donnelly and Pope (1973), and by Heath and Thekaekara (1977) of rocket (and one satellite) observations taken within the past 5 years. The average of different measurements taken during the period 1966-1975 of the integrated solar spectral irradiance at Lyman-α (1216Å) give a value equivalent to about 4.7×10^{-3} Wm^{-2} nm^{-1} (Vidal-Madjar, 1977) -- about the same as the solar irradiance at 1950Å.

The reported range among the different observations is of the order of about ±25 percent for hydrogen Lyman-α; ±25 percent in the spectral interval 1500-1750Å; ±15 percent in the interval 1750-1950Å; ±5 percent in the interval 1950-3000Å. Part of this range, particularly at the shorter wavelengths, certainly represents a real variation associated with solar activity. [Vidal-Madjar (1977) suggests an average observed 27 day solar rotation variation at Lyman-α of ±15 percent.] The remaining observed variation is due to the precision limits of the measurements.

The only selfconsistent set of observations at present of possible time variations of the solar irradiance at different parts of the UV spectrum are those resulting from satellite radiometric measurements on Nimbus III and reported by Heath (1973). The observations indicate total variations over a solar rotation period of about 30 percent at Lyman-α, 5 percent at about 1800Å, and not larger than 1 percent in the spectral region around 3000Å. It is suggested, however, (Heath and Thekaekara, 1977) that a solar cycle variation at 3000Å can be inferred from various observations taken during the period 1964-1975. If real, this has important implications for possible variations of the solar constant associated with solar activity as suggested from the measurements reported by Kondratyev and Nikolsky (1970). It is obvious that high priority

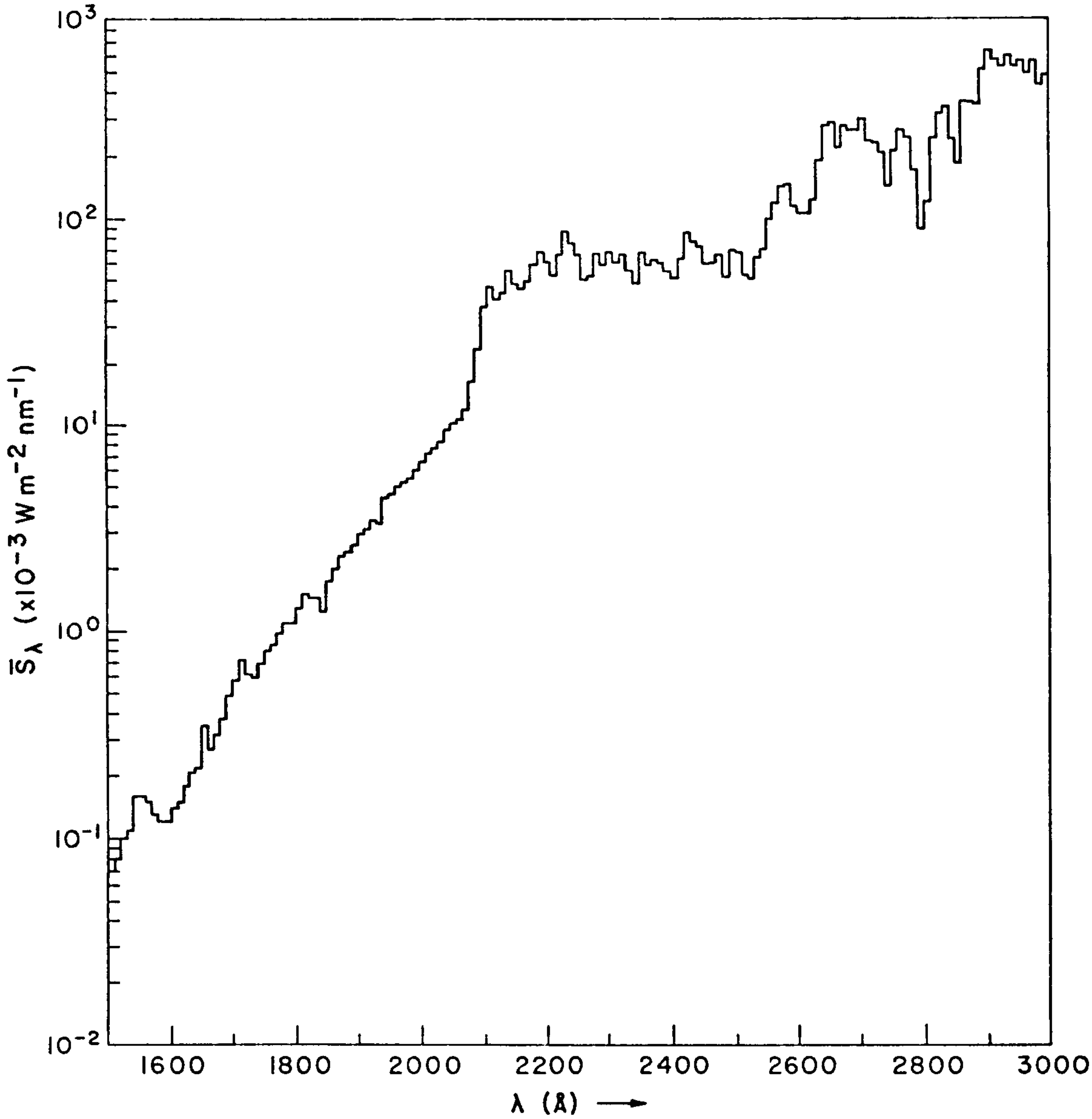

Fig. 1 Solar irradiance in the ultraviolet (1500-3000Å) (After Heath and Thekaekara, 1977; Donnelly and Pope, 1973)

needs to be placed on precise measurements of the spectral irradiance in the vicinity of 3000Å during the coming solar maximum.

As I have mentioned, 99 percent of the sun's radiant energy is contained within wavelengths 0.3 to 4μm. Of this energy, approximately 70 percent is absorbed by the earth-atmosphere system and is responsible for driving the atmospheric heat engine and setting the overall climate of our planet. Although less than 0.2 percent of the absorbed energy is used for various biological processes, recent studies in the United States have emphasized the extreme sensitivity of the biosphere to variations of available solar energy, primarily in the spectral region around 0.3μm (e.g. Grobecker et al., 1974)

Much of the solar energy received at the top of the atmosphere is degraded by extinction processes as it penetrates through the atmosphere. There is significant absorption by ozone in the near UV and by water vapor (beyond 0.9μm) and carbon dioxide (beyond 1.4μm). The optical characteristics of clouds and aerosols also vary spectrally. Since the atmosphere extinction and the earth-atmosphere albedo have strong wavelength dependence, information is required of the spectral distribution of the solar irradiance in addition to the total integrated amount of energy received.

According to a recent consensus of solar and atmospheric physicists (White, 1977) the best presently available data of the solar spectral irradiance in the interval 0.3 to 3μm are those given in Fig. 2. The curve designated by the solid line is based on observations taken mostly by Labs and Neckel at the Jungfraujoch Observatory (at an altitude of 3.6 km). The measurements of Labs and Neckel were of observed solar intensity at the center of the solar disk from which values for the whole disk were inferred by making use of empirically determined limb darkening curves. As is the case for all irradiance determinations from surface measurements, the observed values for the different spectral intervals were extrapolated to zero air mass. The distribution labeled Arvesen et al.(dashed lines) represent an average of measurements made during eleven aircraft flights at a mean height of about 12 km. The values shown as Thekaekara et al. (dotted points) are from a compilation and summary given by Thekaekara of various NASA associated aircraft observations. Only the average of the three sets of values is plotted for wavelengths beyond 1.0μm since the differences in this region would not be discernible on the scale of the graph. The apparent larger variations shown by the data summarized by the Thekaekara et al. is due to the higher resolution of their

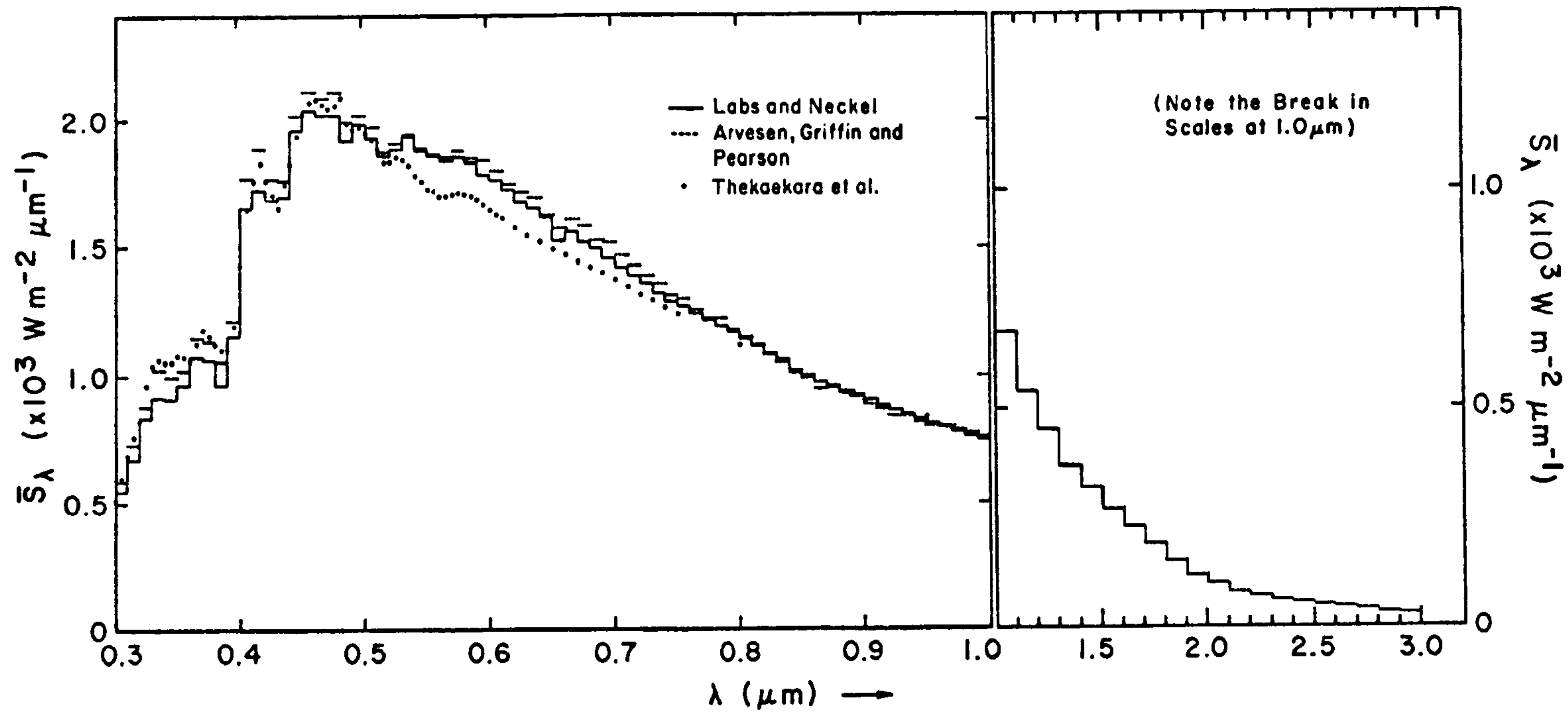

Fig. 2 Solar irradiance in the visible and near infrared (0.3-3μm)
(After Pierce and Allen, 1977)

reported values for wavelengths below 0.6μm. Details of the observational programs upon which these distributions are based is contained in a recent discussion by Pierce and Allen (1977).

The overall accuracy claimed for each of these sets of observations is about ±2 percent (Labs and Neckel); ±3 percent (Arvesen et al.); and ±5 percent Thekaekeara et al. All observations indicate the increasing importance of the solar absorption (Fraunhofer) spectrum at wavelengths shorter than 0.6μm. However, as can be seen from Fig. 2 the difference among the three sets of values can amount to more than 10 percent at some wavelengths -- with the largest difference occurring in the important spectral interval 0.5 to 0.7μm. In the near infrared (beyond 1.0μm) the average difference in the measurements is about 3 percent. Note that above 0.5μm the values given by Thekaekara et al. are uniformally smaller than the other two data sets, but are larger at wavelengths less than 0.5μm. The indicated piecewise internal consistency in the observations would suggest that a major problem involved in bringing the measurements closer together is that of intercalibration of the various observational techniques and the development of a recognized system of absolute standards by which the experimental programs can be compared.

From these and similar observations it is possible to determine the brightness temperature of the Sun at different wavelengths in the visible and near infrared (the region containing most of the solar radiant energy). In this interval the temperature will be above or below the mean photospheric temperature (~5800K) depending on the spectral variation of the opacity of the solar atmosphere. In the region 0.3 to 0.4μm the brightness temperature is of the order of 5500K because of the strong Fraunhofer absorption; about 5800-6000K in the region 0.5 to 1.0μm and a peak of about 6400K at 1.4 - 1.8μm. This latter maximum in brightness temperature is a result of the decreased photospheric absorption (decreased opacity) by H^- at this wavelength. Thus, the solar emission originates from a deeper and warmer region of the photosphere. Possible variations in the irradiance at this part of the solar spectrum (which still contains about 7 percent of the solar radiant energy) need to be identified since atmospheric absorption by water vapor and carbon dioxide becomes effective at these wavelengths.

As I have stated, it has been suggested that there is an observed variation of the solar constant of the order ±1 percent associated with sunspot occurrence such that the solar constant is small for low and high relative sunspot numbers (e.g. Kondratyev and Nikolsky, 1970). However, there seems to be no theoretical justification on the basis of our present understanding of the physics of the Sun for a variation of the solar irradiance in the visible solar spectrum, directly associated with sunspots, larger than about 0.1 percent (Smith and Gottlieb, 1974). Nor is there any apparent reason why the solar constant variations should take the form implied by Kondratyev and Nikolsky. A major problem at present for solar physics is to determine what are the dynamic processes which contribute to the variability of the Sun if, indeed, it is variable. A resolution of these problems is of fundamental importance to both atmospheric and solar physics and I would like to reiterate and emphasize the need to carry through the recommendations made at each of the meetings of the Radiation Commission for at least the past 15 years. Namely, that a monitoring program of the solar constant be instituted with a precision capability of the order of a few tenths percent.

In addition, it is clear that we will not be able to remove or understand this apparent discrepancy between theoretical estimates and observations unless the spectral distribution of the solar irradiance is monitored at the same time.

Calculations of the various components of the earth's energy budget requires accurate input information of the solar irradiance at these wavelengths where absorption plays a significant role in the large scale dynamic behavior of the atmosphere, particularly as it affects climate. For understanding possible solar effects on climate variability, long term observations with high relative accuracy (i.e., observational systems with good stability and high precision) would be needed. The required absolute accuracy is of the order of at least 0.5 percent for the solar constant. The accuracy for the spectral irradiance is better than 5 percent in the near UV (1950-3000Å) and 1 percent in the visible and near infrared. The relative accuracy needs to be at least half of these values.

Although ground-based observations have and will continue to have some important advantages over other systems, major efforts need to be made for the use of space platforms for future observational programs. The planned space shuttle and other satellite systems to be launched for the upcoming solar maximum in 1978-79 afford an excellent opportunity for such observations. Information on solar variability can then be acquired through carefully calibrated measurements made over several solar rotations and all efforts should be made to launch satellites during this period that will have at least a one year lifetime. During this period of satellite observations inflight intercalibrations should be made through coordination with a program of rocket observations having duplicate equipment of that used in the satellites. An international system of standardization and calibration needs to be vigorously pursued so that results of observations made with different systems at different times can be equated. Unless such a calibration and intercomparison program is now developed, we will continue to have difficulties in interpreting recorded variations in the data.

The atmospheric sciences thrive from the fact that they can take advantage of cumulative knowledge. We are now in a position of using that knowledge as a basis for obtaining much more information within the next four years which will provide highly accurate values of the solar irradiance and their temporal variations. I suggest that we plan a session for the next symposium of the Radiation Commission to listen to and evaluate these results.

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