7. RADIATION BUDGET AND RELATED MEASUREMENTS IN 1985 AND BEYOND

7.1 INTRODUCTION

Recognizing the need to begin conceptual design of the follow-on programs to ERBSS, a group representing various science, engineering and government planning segments considered the next steps in radiation budget and cloud measurements. The results of their deliberations, targeted toward satellite "System 85" now being formulated by NASA and NOAA, are summarized in this section.

The Working Group chose terms of reference from the recent U.S. GARP report "Elements of Research Strategy for the U.S. Climate Plan" (1978). They included a focus on study of the annual cycle of radiation and cloudiness as well as its variability. The observing system plan in the referenced document provides background for the following discussion.

The highlights of this Working Group's discussions and recommendations are summarized as follows:

(a) Identification of users of radiation budget and cloud data should be continued with greater effort and the broad base of user interest, as evidenced by the present workshop, should be actively maintained.

(b) Data from past, present, and future systems must be made readily accessible to users by using more efficient methods.

(c) Future radiation budget and cloud measurements should be obtained by the use of composite measuring systems. ERBSS is a good example in this regard. Future systems will include use of multiple orbits, Spacelab flights, and ground truth measurements.

(d) Temporal and spatial sampling is the major cause of uncertainties in present radiation budget systems. To reduce these uncertainties, multiple satellites in different orbits are required. Final combinations of orbit inclinations can be computed depending on the user emphasis. A system of 1 or 2 Sun-synchronous satellites is inadequate to determine the Earth's radiation budget in view of the science requirements. The optimum set of 2, 3 and 4 satellites for the radiation budget system beyond 1985 is yet to be determined. ERBSS is a key experiment leading to the specification of future systems.

(e) Instrumentation needed for radiation budget and cloud measurements, which will be needed in 1985 and beyond, is presently available, with small improvements in its reliability, stability, and lifetime expected in the next few years. A special study of such instruments is warranted.

(f) Measurements needed in the post-1985 period include estimates of the radiation budget at the surface, estimates of the net heating profiles in the atmosphere, and measurements of solar spectral radiance.

The Working Group was appreciative of NASA and NOAA cooperation to form a Radiation Budget Program. The group drafted a letter in this regard to be sent to those presently studying System 85. The group favored the idea of experiment teams, and recommended continuation of scientific and engineering competition to maintain a healthy diversity of effort focused toward future radiation budget and cloud measurements.

The following sections provide more details of the discussion and opinions which led to the summary statements above.

7.2 RELATED MEASUREMENTS

In addition to the need for broadband radiation measurements of the type to be provided by ERBSS, the need also exists for measurements of radiation budget in various spectral bands, surface radiation budget, and cloud heights and properties, and for solar monitoring, both of the total power output and in various spectral ranges. The next few sections discuss these needs.

7.2.1 Spectral Measurements of Radiation Budget

Lack of spectral uniqueness of reflected solar radiation by satellite-based instruments poses the question of an appropriate measuring device for inferring the Earth radiation balance. Portions of the reflected solar spectrum are dominated by varying degrees of particulate scattering, by the absorption bands of the near-infrared, and by the absorption properties of the reflected solar radiation as measured by a broad-barrel radiometer. Measurements are needed in narrower spectral intervals. This may be done in either the primary radiometer used to determine the Earth radiation balance, or in a separate instrument on the same satellite.

Similarly, measurements of Earth emitted radiation in selected spectral bands are needed. Climate modelers wish to check their model radiation calculations in key CO_2, H_2O, chlorofluoromethane (CFM) bands, etc., to insure that their radiation models are adequate. For monitoring, a CO_2 doubling would decrease 12 to 18 µm radiance, but increase 4 to 12 µm! In addition, it may be possible to determine the flux divergence of infrared and solar energy *in the atmosphere* by use of spectral data. Additional discussion of these points is given in Appendix C entitled, "Satellite Radiation Budget Measurements in Spectral Bands," by V. Ramanathan.

It is recommended that *instrument concept studies be initiated for measurements of the spectral distribution of reflected solar radiation and of broadband Earth thermal radiation. Consideration should be given to inclusion of these measurements in the design of future systems for determining the Earth radiation balance.*

7.2.2 Solar Monitoring

The generally accepted theory in the evolution of stars, such as our Sun, predicts that the solar luminosity should change only on a time scale of billions of years and requires an increase of only 30 percent from the time of formation of the Sun to the present. This theoretical stability is based on the assumption that the nuclear reactions ultimately responsible for producing the energy emitted from the solar surface proceed at a steady state.

This classical theory has come under severe strain in the last few years following the surprising discovery that the Sun is apparently emitting only a *very* small fraction of the flux of neutrino particles that theory predicts. One way out of this dilemma is to suppose that, for some reason, the Sun is not now in a steady-state condition, but rather is in the midst of some disturbance. Such an assumption would also allow the conclusion that for the same, or another unknown reason, the irradiance may also vary with the state of perturbation. As yet, a satisfactory theory does not exist that can account for such fundamental solar phenomena as the 11-year sunspot cycle or the 22-year magnetic cycle, nor for most of the highly complex solar features that can be observed on the Sun. Yet, some of these features are known to have casual connection with changing conditions in the Earth's magnetic field and the state of the upper atmosphere and it does not seem possible to rule out solar variability on a theoretical basis.

Evidence of variability. Differential photoelectric measurements of sunlight reflected from Uranus and Neptune can be made that are accurate to a small fraction of 1 percent by comparing their magnitudes with stars of similar brightness and color located nearby in the sky. Two sets of such data spanning 25 years were reported on by Lockwood who concluded that a brightening trend has been in progress for Titan, Uranus, and Neptune since at least 1972. He further states that ". . . no reasonable explanation for the cause of the brightness variation is evident that does not involve the Sun, directly or indirectly, as the causitive factor."

The rate of carbon 14 production also indicates that variations in total solar irradiance have occurred in the past. Radioactive carbon dating, when applied to samples of known age, such as wood samples of well-known chronology, results in errors of the order of decades because the rate of production of C^{14} in the atmosphere has apparently not been constant. For example, between 1300 and 1800 A.D., there is evidence that the proportion of C^{14} in the atmosphere was between 1- and 3-percent more than at present.

If variations over long periods of time have occurred in the past, then the possibility of variations over shorter periods, such as 10 to 30 years must be considered. In this connection, it is noted that the sunspot activity of the 11- and 80-year cycles tends toward rapid onsets followed by slow dropoffs in activity, and light curves of pulsating variable stars also exhibit this characteristic.

Climate sensitivity. Budyko estimates that a 1 percent change in solar radiation could result in a change of 1.2°C to 1.5°C in the mean temperature of Earth's surface. The Study of Man's Impact on Climate (SMIC) report states ". . . a change of solar radiation of 1 percent, with cloudiness equal to 0.5 and present global albedo, changes the mean temperature of the Earth by 1.5°C." Similar estimates for a change in the mean temperature of the Earth as a result of solar radiation have been given by Sellers, Manabe, and Wetherald.

Several scientific bodies have recommended a long-term program aimed at monitoring the total solar flux to an accuracy of a fraction of 1 percent. The recommendation of the National Academy of Science/Committee on Atmospheric Sciences *Ad Hoc* Panel to review the NASA Earth Energy Budget Program follows. "Monitor solar output, integrated over wavelength with long-term precision of 0.2 percent or better and absolute accuracy of 0.5 percent or better."

Present absolute radiometers. Present technology in radiometers for measuring the total solar flux is adequate to meet these requirements and several different designs currently exist. These radiometers are primary standards in themselves in that more accurate reference instruments for calibration purposes do not exist. Yet small, but significant, differences between these instruments do exist.

For example, the Nimbus 6, launched in June 1975 carried a solar flux radiometer that produced measurements approximately 1-1/2 percent higher than expected based on measurements made by other absolute radiometers. Because of this disparity, two absolute radiometers, each of different design, were flown into space aboard a single rocket in June 1976 and their measurements were compared with those of Nimbus 6. The difference between the lowest and highest values from this flight was 5 Wm^{-2}, and the capability of present instruments to meet the ERBS requirements was demonstrated. However, the Nimbus 6 instrument measurements were found to be too high and the need for direct intercomparisons between absolute radiometers was finally established.

Solar spectral determinations. Although it is well established that large and climatically significant variations occur in the solar ultraviolet (UV), the magnitude and periodicity are not well defined. The predominant effects of UV changes are a variation of upper atmospheric heating, which may affect atmospheric circulations, and an alteration to ozone budgets which, in turn, affect stratospheric chemistry. Whether significant variations occur at longer wavelengths is not as well established. Changes in the long wavelength spectrum, if they occur, would impact lower atmospheric heating in the water vapor bands.

Infrequent spectral observations through an atmosphere with variable attenuation with instruments having differing spectral resolutions and measuring concepts leave the magnitude and periodicity of all spectral variations uncertain. Clearly, observations from space are essential and the development of standard calibration procedures and reference standards a must.

The following recommendations are made:

1. *Immediately initiate a rocket/shuttle/spacecraft program to establish solar baseline UV levels during solar maximum (1979-81).*

2. *Develop instruments to determine the magnitude of solar variability in the water vapor absorption bands and perform periodic measurements over one solar cycle.*

3. *Establish a national laboratory, building on NBS expertise, to calibrate instruments measuring solar wavelengths.*

7.2.3 Measurements of Cloud Heights/Cloud Properties

Clouds are good absorbers of infrared (IR) terrestrial radiation and reflectors of solar radiation. They are a major factor in determining the Earth's radiation balance. The lower temperature cloud tops replace the higher temperatures of the Earth's surface as emitters of IR radiation to space and thus reduce the outgoing radiation. Also, the amount of cloud cover determines the total solar radiation reflected from the cloud tops. For example, a globally averaged model showed that global changes in the cloud amount of a few percent or in the cloud top height of a few hundred meters could cause a variation in the global mean surface temperature by about 1° C. This change is also dependent upon cloud type. A clear definition of cloudiness (height, amount, properties) consistent with observations and suitable for models is required.

The satellites expected in the System 85 group should be designed to provide the necessary information on clouds. Improved sounders and scanners can provide the required observations. It is possible to devise cloud heights and properties by applying physical-statistical methods to measurements made in different spectral intervals. Some techniques are already available at the present time to extract such information and improvements to these methods are needed.

Another method of obtaining cloud height information is by utilizing the measurements from two geosynchronous satellites over the overlap regions. Images of cloud elements observed from the two geosynchronous satellites could be subjected to stereoscopic techniques to obtain cloud heights. This technique is limited only to overlap areas.

In order to obtain more meaningful information on the cloud properties, it is essential to supplement the satellite measurements with adequate surface observations. Lidar and other sounders located on the ground should be used in conjunction with the satellite information to obtain more information on the cloud structure.

It is recommended that *techniques should be developed to extract cloud height, amount, and properties information from the current satellite sensor systems and after examining the results, if necessary, suggest the appropriate recommendations for the group (System 85) charged with the development of a new system.*

7.2.4 Measurements of Surface Albedo and Surface Radiation

Rationale. The scientific community has emphasized the importance of surface radiation and surface albedo (including solar insolation and infrared) to climate studies. (See Climate Modeling chapter.)

Recommendation. It is recommended that *a special study be conducted leading to the capability to measure surface radiation budget from satellites by 1985. Two tasks are proposed:*

Task 1. Assess the ability to determine from satellites:

(a) The solar energy reaching the ground.

(b) The solar energy reflected from the ground.

(c) The infrared emission from the ground.

(d) The infrared sky radiation.

(e) The net surface radiation budget.

Task 2. Suggest instrument modification and/or development to improve the determination of (a) to (e) of Task 1. Develop and validate instruments, if required.

Implementation plan. The implementation of Task 1 would require the coordinated efforts of many organizations and university groups. The following case studies could be performed:

(a) Selected locations in tropics, mid-latitudes, and near polar.

(b) Winter and summer.

(c) Land and water.

(d) Top-of-the-atmosphere radiation from NOAA, GOES.

(e) Surface radiation from aircraft flights and NOAA network for solar energy.

(f) Radiative transfer modeling.

(g) Surface truth sites or ships.

Use the results of Task 1 to begin work on instrument modification and/or development. A special study should be planned in the 1978-1979 time period with the aid of an announcement of opportunity. The studies should be completed by late 1980.

7.3 PROGRAM IMPLEMENTATION

The recently approved National Climate Program provides the opportunity and impetus for a coherent program for development of measurement concepts, instruments, and systems for climate observations and for use of these systems so as to insure adequate or optimum observations. It is recommended that *the following policies be actively included in planning implementation of the climate program.*

1. Define the climate measurement requirements well in advance as an integral part of a climate program.

2. Develop a program to design, test, implement, and maintain the required measurement concepts, instruments and systems.

3. Establish a competitive selection procedure that will encourage the infusion of new ideas and technology into the observation program.

Before the science requirements for Earth radiation budget beyond 1985 can be established, it is necessary to identify the users. The next section discusses the continuing problem of user identification. Because of the wide range of radiation budget data users and the mass of data being gathered, data access is then considered.

The major facets of the program are instrument development; sampling studies to define the requirements for adequate observations; and system studies to determine the combination of balloons, aircraft, ground-based and satellite measurements needed to meet the science requirements. These facets are discussed in the final sections.

7.3.1 User Identification

To define the radiation budget measurement system for 1985 and beyond requires some knowledge of user community requirements for the same time frame. Unfortunately, little has been said about these future needs. It is apparent, however, that the comprehensive climate program plans being developed in national and international fora will require more accurate, better conceived, and more extensive observations of the radiation budget than are now being received or even proposed.

At present, there are several foci for users of Earth radiation budget data to be identified. These foci include the developing World Climate Program under the World Meteorological Organization (WMO), the Global Environmental Monitoring System being developed by the United Nations Environment Program (UNEP), activities by International Council of Scientific Unions (ICSU) and the United States Climate Program now being considered for endorsement and support by the Congress of the United States.

These major programs cover a wide range of potential users for Earth radiation budget data. There are applications in climate research, impact assessment, and forecast preparation. It is hoped, for example, that statistical models now being used for preparing monthly and seasonal climate outlooks by the National Weather Service may improve these and longer term projections by incorporating Earth radiation budget data supplied in "real time." By 1985, Earth radiation budget data will be incorporated in a comprehensive "current awareness" of the global climate state, to be made available to a large user community through the U.S. Climate Program's proposed Climate Analysis (sic Diagnostics) Center.

The U.S. Climate Program Plan encourages assessment of climate impacts on food production, energy and water resource development, distribution, and use, among a host of other possible affected socioeconomic systems. Thus, it is anticipated that further demands for radiation data will be made, but they have not yet been articulated. Similar requests may come from related international programs of Food and Agricultural Organization (FAO) and UNEP.

By far the user group which has given the most thought to what radiation budget data may be needed in 1985 and beyond is the research community--those who seek to understand complex climate processes and the physical mechanisms for effecting climate variations. This user group has stated its requirements in previous documents such as the WMO/ICSU report, The Physical Basis of Climate and Climate Modeling, and more recently in a NASA report, Elements of the Research Strategy for the United States Climate Program.

There are many uses to which Earth radiation budget data may be applied in climate research. Long-term field research programs aimed at understanding specific climate processes, such as ocean-atmosphere energy exchange, have a certain set of Earth radiation budget data requirements; yet, a hierarchy of climate models now being developed may have somewhat different sets of requirements for Earth radiation budget data. Those researchers working on parameterization of radiation budget components for climate models, and those comparing the real world with model climate simulations are part of the ERB data user community. Modelers involved in sensitivity experiments and experiments to gain insight into possible inadvertent, anthropogenic modification of climate will require better knowledge of radiation budget components.

It is clear that the user community has not made an adequate statement of requirements for Earth radiation budget data beyond 1985. This is, in part, due to the very recent emphasis on connecting such a comprehensive list of potential users as indicated in the aforementioned climate programs. It is also true that as research progresses (in understanding the physical basis for climate, in improving forecast techniques, and in expanding utilization of climate information for assessing climate impacts on social, economic and environmental systems), requirements and the user community will change. It is recommended that *efforts be continued to identify present and potential users of ERBSS data and their requirements.*

7.3.2 Data Access

Earth radiation balance values are inferred from satellite measurements rather than being direct measurements in themselves. There are, therefore, two levels of research associated with these data: that involving the process of deducing the individual radiation balance values; and that which applies the values as climatological means. The former is complicated by models which transform rudiments to fluxes. These must account for inferences of the bi-directional distribution employed in the transformations. Cloud heights, amounts, and vertical and horizontal distributions; diurnal variations of surface temperatures and clouds; and the adequacy of atmospheric sampling typify possible errors which may be propagated into the climatological means. To overcome or to minimize these sources of error, continuing research will be needed.

As supplements to the ERBSS-type measurements, data from other spacecraft instruments will, to varying degrees, be needed for studies of appropriate models and for direct application of the models in the process of deducing the radiation balance data. These studies will require ready access to a body of Level 0 and Level I data as defined in Table 14 of the NOAA Climate Program (December 1977). Inasmuch as the volume of these data can quickly reach unmanageable proportions, a program of systematic collection of suitable samples must be defined, and the data sets should be placed in the archive in a form which will provide ready access to the research group.

The NOAA Climate Program, in its portion on Data Management, has recognized the scope of data access. With the steadily increasing magnitude of data sets, the possibility exists that a gap will arise in the communication by the research community with needed archived data to meet special requirements.

In recognition of the rapidly changing technology of data storage, and in recognition of the role of research activities in support of an operational climate program, it is recommended that *special consideration be given to the needs for rapid access of Level 0 and Level I data sets from satellite instruments measuring radiation balance and related parameters.*

7.3.3 Instrument Development

The basic instruments of Earth radiation budget observing systems measure (1) total solar irradiance, (2) reflected solar flux, and (3) total infrared flux. The latter (Earth flux) measurements require wide and medium field of view (FOV) radiometers and narrow FOV scanners to aid in deconvolution of flux data to fluxes at the 30-km reference altitude.

Present technology of the type used on the NIMBUS-6 and NIMBUS 7 ERB experiment and planned for ERBSS appears to provide useful accuracy for climate studies up to the mid-1980s. In fact, as noted elsewhere, the accuracy limitation up to that point in time will be due to inadequate diurnal sampling, not instrumental errors. Beyond 1985, it is anticipated that, with the reduction of sampling errors and improvements of climate models, instrumental limitations will become relatively more significant. *Development of improved instrumentation to meet the more stringent requirements of the mid-1980s should begin immediately.*

Determination of net radiation budgets over a range of space and time scales with long-term continuity requires consistency between solar and longwave measurements, among narrow, medium and wide FOV measurements, between solar irradiance and Earth flux measurements, between different or replacement satellite systems, and between in-orbit remote measurements and surface based or *in situ* measurements. This consistency will not be achieved without careful planning and considerable effort. *Thus, development of a comprehensive system for calibration, intercomparison and standardization of all energy budget radiometers should be given highest priority. Special attention should be directed to the calibration of shortwave wide and medium FOV radiometers and shortwave narrow FOV scanning radiometers.* The system must also be prepared to deal with problems presented by special instruments designed to measure in split spectral bands or other auxiliary instruments to insure their consistency with the basic instruments.

Also, high priority should be given to development of improved wide and medium FOV radiometers to provide:

(a) long-term in-orbit stability

(b) reliable in-flight calibration

(c) accurate separation of shortwave and longwave flux components.

(d) spectrally flat response within each spectral band

(e) ideal/well-defined angular response

Adaptation of electrical compensation cavity detectors to wide and medium FOV radiometers should be supported as a primary means to achieve these objectives.

Development of improved instrumentation for in-flight calibration of shortwave scanning radiometers is needed. Study is also needed for defining a ground truthing program, which might include in-flight comparisons including shuttle underflights, and shuttle return flights.

7.3.4 Sampling Problem

Earth albedo and longwave emitted radiation vary significantly with time and geographical location. Obtaining accurate measurements of Earth radiation budget requires spatial and temporal sampling that accounts for variations in solar zenith angle, cloud conditions, and surface features. Multiple satellites in different orbits are required to obtain adequate temporal sampling of regions at various latitudes and longitudes. Two satellites in Sun-synchronous orbits provide coverage only at two and four local hours for shortwave and longwave, respectively. However, satellites in mid and low inclined orbits could be combined with Sun-synchronous satellites that are flown with a near noon equatorial crossing time, when the radiation energy level is high, rather than with early morning or late afternoon crossing times as is done with weather operational satellites. Other combinations of inclinations should be fully studied to determine the optimum system of satellites. Both low and geo-synchronous altitude satellites should be included in this analysis. Final recommended combinations of orbit inclinations would depend upon the "user" emphasis. Emphasis of tropical regions would indicate a low inclination orbit. Emphasis of equal areas globally or land masses would indicate a mid inclination orbit. Both options would include a high inclination orbit to cover the high and polar latitudes. Extremely high accuracy or shorter time averages (less than monthly) will probably require at least three satellites (for example, high-, mid-, and low-inclination orbits). Dramatically improved diurnal models for several latitudes might allow one to use only Sun-synchronous orbits. However, because of cloud variability and its effect on diurnal models, it is doubtful that this will be realized.

Other quantities which are strongly related to Earth radiation budget and for which sampling problems must be considered are surface radiation, clouds, solar spectral distribution of radiation and total solar radiation. The sampling requirements of surface radiation appear comparable with those for Earth-emitted longwave and reflected shortwave radiation. Studies which relate surface radiation budget to that of the top of the atmosphere should be considered. Also, the technology should be developed to measure surface radiation budget from spacecraft. Work is needed to define the observational requirements regarding clouds, so that the sampling problem for clouds can be treated. A major consideration here is to keep the data handling and processing requirements within reasonable bounds. The sampling problem for solar spectral distribution and total solar radiation appears to be an order of magnitude simpler than that for the previous parameters, because a geographic distribution is not required, and also because the changes with time are not nearly so rapid.

7.3.5 Composite System

To observe the Earth's radiation budget parameters after 1985 will require a composite system made up of some combination of balloons, aircraft, ground-based and satellite-based measurements. For instance, some parameters can and should be measured globally, over long periods of time. Examples of these parameters are total solar flux and ultraviolet radiation, net radiation budget at the top of the atmosphere, and cloud cover. Other parameters such as surface radiation budget and cloud properties are more easily observed by *in situ* or near *in situ* means. System 85 should be planned and implemented in conjunction with evolving science and operational requirements. The preparatory phase should

1. Foster further instrument development including cavity radiometers.

2. Study sampling problem in considerable detail to:

   (a) Select a system (satellites, balloons, or ground-based or combinations)

   (b) Develop best possible fields (longwave and shortwave) from NIMBUS 6 and 7 to use for sampling studies (including field coherences)

   (c) If a satellite system is required, develop optimum orbits or combination of orbits:

       Sun-synchronous
       high inclination
       medium inclination
       low inclination
       Earth synchronous

   (d) Study Synchronous Meteorological Satellites (SMS) and other systems to determine how they can be used in conjunction with System 85.

3. Develop calibration/ground truth strategies including shuttle underflights and shuttle return flights.

4. Include periodic shuttle flights to validate instrument, calibration, data reduction, data analysis, and data utilization concepts.

5. Develop model/data interaction schemes to utilize past data and aid in planning System 85.