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RADIATION BALANCES AND THE SOLAR CONSTANT

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RADIATION BALANCES AND THE SOLAR CONSTANT*

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SUMMARY

After defining the radiometric concepts which are necessary, we consider various types of radiation balances which are of scientific interest and relate them to the diabatic form of the energy balance. After this, after demonstration the wide variability in space and time of the components, we demonstrate the difficulties of the problem both in terms of components determined on the ground and the components determined from satellites. We then propose a specific concept for sweeping which is tailored to the requirements. Finally, after establishing the truncated character of our present knowledge of the radiation balance, we give the result of the last observations of the solar constant.

Key words: radiation balance, energy balance, solar constant, optimum scanning.

1. INTRODUCTION

A considerable effort has been expended since the beginning of the Space Age measuring the components of the radiation balance. At the present time, we can consider the problem to have been essentially well posed, but still far from being solved. The objectives are not always sufficiently well defined and, in general, expenditures and efforts required for solving the problem are usually underestimated.

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Since we have now gone beyond the limits of simple exploration, it would now be necessary to assure an optimum utilization of the observations and also to master various numerous difficulties which have to be overcome. The most important one is to provide the synthesis of the required means on a solid and objective basis.

This is certainly a difficult area. The radiation field has a space-time variability as well as a spectral variability which is very wide. The metrology of the radiation parameters is still being developed and the comparability of observations made up to the present is still very problematical.

Certain interesting conclusions can be made such as the shadowing towards the edge of the albedo and the non-isotropic character of the reflected radiation. Maps of radiated radiation, of the albedo and the radiation balance established over 15 years for the entire world have been published from particular observation conditions.

The purpose of this short note will be to define the radiometric concepts and to formulate the problem of the radiation balance within the context of the energy balance, and then to describe the difficulties which have to be overcome.

2. DEFINITIONS OF RADIOMETRIC CONCEPTS

In order to introduce the notion of the radiation balance, it is interesting to consider as a point of departure the energy balance equation formulated in the diabatic form for a point and a given time in the atmosphere.

It is written as:

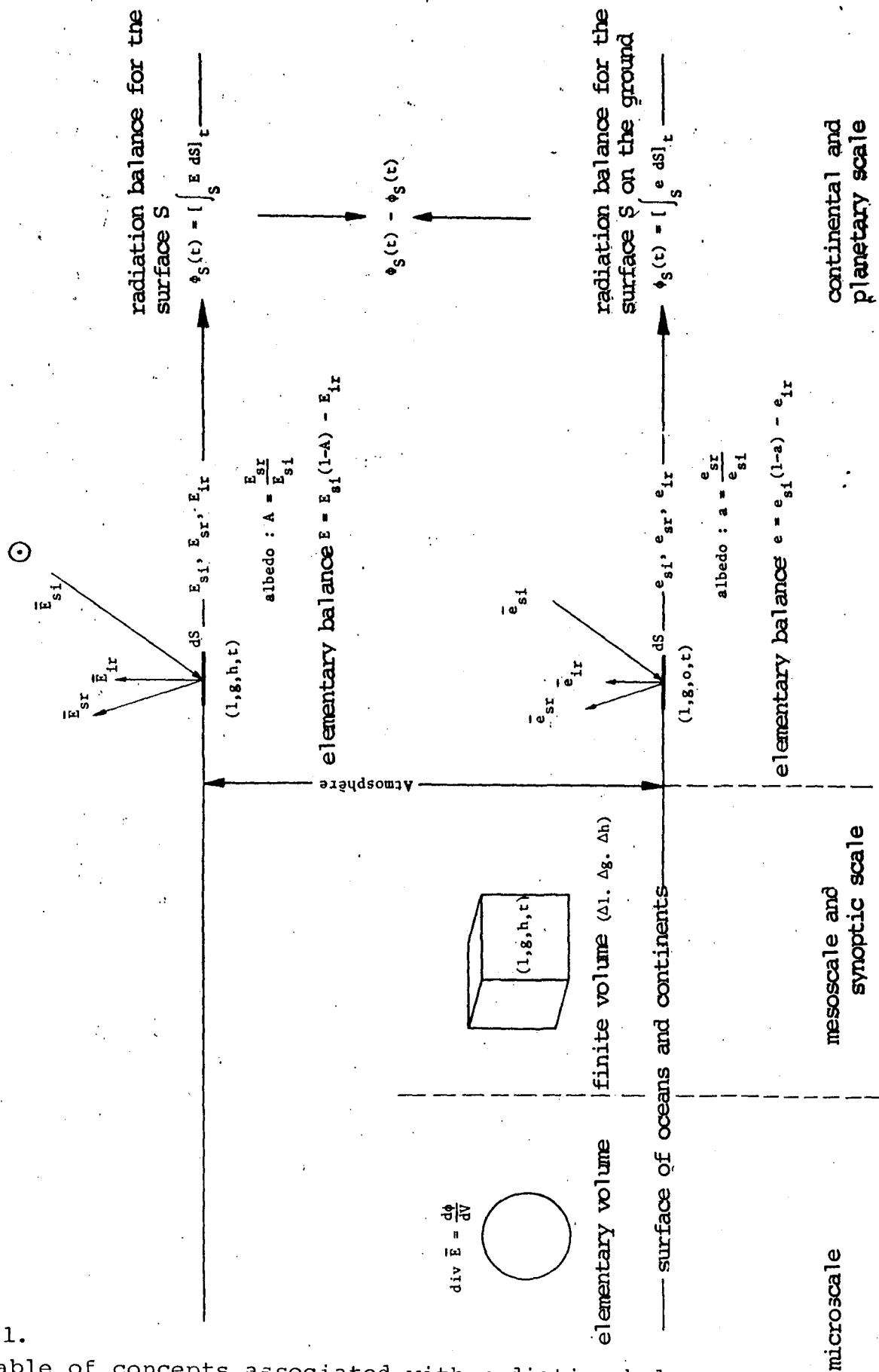


Figure 1.

Table of concepts associated with radiation balances.

$$p R^{-1} T^{-1} \left(\sum_i \tau_i C_{pi} \frac{dT}{dt} + \sum_i h_i \frac{d\tau_i}{dt} \right) - \frac{dp}{dt} = - \operatorname{div} \bar{E} + \frac{dq_{lat}}{dt}$$

with p and T are respectively the pressure and the temperature, τ_i is the mass concentration of the constituent i , C_{pi} is the mass heat at constant pressure of the element i , h_i is the mass enthalpy of the element i , $\operatorname{div} \bar{E}$ is the divergence of the radiation at the point and the time under consideration, dq_{lat}/dt is the source of the latent heat.

\bar{E} is the vector resulting from the various components of the radiation field, the direct solar radiation, the reflected solar radiation and the diffused solar radiation, the infrared terrestrial radiation emitted or reflected and diffused by the ground and the atmosphere, including clouds;

$\operatorname{div} E$ is, therefore, the difference between the incident radiation and the radiation which leaves the elementary volume; this is one of the components of the source or the sinks of heat (expressed in Wm^{-3}) which are responsible for the dynamic behavior of the elementary air volume.

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We can easily see that the adiabatic hypothesis should be introduced very rapidly from the formulation of the system of equations which describes the dynamic behavior of the atmosphere. This is because the atmosphere state represented by the field of the variables p , t , ρ , u , v , w is already excessively complicated. Therefore, source and sink terms are problematical, and we even do not have observations for them.

This paradox situation was especially well described by L. J. L. Deij and J. Van Mieghem. They saw the requirement for

establishing an observation network of the components of the radiation field. This would have meant that the energy balance equation would have become very important because it is the only relationship between the heat sources and the circulation which results from their distribution.

By applying the Green Ostrogradsky theorem to the sources or sinks of the energy balance equation, and after integration of each of the terms over the volume V, we then find the concept of the radiation flux.

In effect,

$$\int_V \operatorname{div} \bar{E} dV = \int_S \bar{E} \cdot \bar{n} dS$$

where the flux density $\bar{E} \cdot \bar{n}$, which is a variable expressed in Wm^{-2} must be considered at each of the points of the surface which surrounds the volume V.

Let us note that $E = \bar{E} \cdot \bar{n}$ is the density of the net flux, that is, the difference between the incident flux densities to either side of the plane perpendicular to \bar{n} at the considered point of the surface S. This is the density of the radiation balance or the elementary radiation balance.

Therefore, the integration over the volume V determines the radiation balance for this volume, that is, the energy which is stored in the form of internal energy and which will be transformed into kinetic or potential energy.

The integration volume fixes the space scale selected, micro-scale or mesoscale, synoptic scale or planetary scale. Out of the two phases parallel to the Earth's surface and the others which are in general selected vertical, one of them is always the lower limit and the other is always the upper limit of the troposphere.

No matter what face is considered, the flux is decomposed according to its components corresponding to the solar spectrum (subscript s) and the infrared emission spectrum of the ground surface, of the clouds and of the atmosphere gases (index ir), as follows:

$$\phi_s = \int_S \bar{E} \cdot \bar{n} \, ds = \int_S (\bar{E}_s + \bar{E}_{ir}) \cdot \bar{n} \, ds$$

where $\bar{E}_s = \bar{E}_{si} + \bar{E}_{sr}$ and \bar{E}_{si} is the vector resulting from the incident solar radiation (direct and diffused) and \bar{E}_{sr} is the vector resulting from the solar radiation reflected by the surface. The albedo of a discontinuity surface is defined as being the ratio of the reflected flux density and the incident flux density

$$A = \frac{\bar{E}_{sr} \cdot \bar{n}}{\bar{E}_{si} \cdot \bar{n}} = \frac{E_{sr}}{E_{si}}$$

This allows one to express the net flux density E_s as a function of the incident flux density and as a function of the nature of the discontinuity surface $E_s = E_{si}(1-A)$.

The infrared net flux density E_{ir} will depend on the temperature and the emission factor of the sources located to either side of the plane under consideration.

Finally, let us recall that the solar vector E_s and the infrared vector \bar{E}_{ir} result from the integration of their respective spectral distributions.

If instead of considering the resultant of all of the radiation vectors we only consider the vector which comes from a given direction, we will then speak of the intensity of the source in this direction ($W \cdot Sr^{-1}$).

3. RADIOMETRIC PARAMETERS AND THEIR SCIENTIFIC IMPORTANCE (see Figure 1)

The concepts which have been defined above allow one to show how they are involved in the problems of various areas of geophysics and the physics of the atmosphere.

On a microscale level, the knowledge and continuous observation of the divergence of the radiation will allow one to better understand the dynamics of the atmosphere on the scale, and especially in the vicinity of the discontinuity surfaces (ground, clouds) where the local thermodynamic equilibrium is interrupted or where the radiation field plays primarily the role of a motor.

On the mesoscale level and the synoptic scale, we would not expect a very fast evolution of the present situation because a great deal of time will be required without any doubt before the observation data of sources and sinks will be available on a space-time density level required. Nevertheless, experiments such as, for example, those under the radiation sub-program of Gate are extremely important in order to aid in the formulation of models as a function of particular regional conditions.

At a much larger scale, when the vertical surface of the atmospheric volume under consideration is negligible compared with the horizontal surfaces, it is necessary to determine the net flux for the upper surface of the troposphere as well as at the ground level. The radiation energy ϕ_S which is given up on the ground at the time t is given by the relationship

$$\phi_S = \int_S [e_{si}(1-a) - e_{ir}]_t ds$$

It depends on the albedo a , which varies according to the nature of the ground. The elevation of the sun and the diffuse/global radiation ratio, the global solar radiation e_{si} itself is variable depending on the cloud cover and the time of day. Finally, e_{ir} is the infrared flux density which depends on the temperature and the emissivity of the ground, of the atmosphere and of the clouds. The flux ϕ_S will have an effect at the level of the ground

temperature and more particular, will affect the climate.

At the upper surface of the atmosphere, the energy given up at the time t to the atmosphere plus ocean system and continent system is given by the following relationship:

$$\phi_s = \int_s [E_{si} (1 - A) - E_{ir}]_t ds$$

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Here the albedo A as well as E_{ir} at a given location depend primarily on the nebulosity. The entering radiation E_{si} depends only on the elevation of the sun and for a residue of about 6% of a year. The solar constant is what determines E_{si} .

We can see that for the requirements of atmospheric physics, it is the difference $\phi_s - \phi_S$ plays the most dominating role for maintaining the atmospheric dynamics and the regional climate conditions associated with ϕ_S .

As far as climate proper is concerned on the ground, the average of the term ϕ_S will be determining. The judicious selection of the integration time will allow one to demonstrate the natural astronomical periodic variations and also those which represent a significant climatic tendency.

On a planetary scale, the climate of the Earth will depend essentially on the average of ϕ_S integrated over the entire Earth surface.

4. VARIABILITY OF THE RADIOMETRIC QUANTITIES

The main problem which one encounters when one wishes to take into account the radiation field in order to evaluate its effect on other physical parameters which determine the state of the atmosphere is to obtain representative measurements. The difficulty comes from the extreme variability in space and time of the radiation

field, which is then the origin for the dynamic behavior of other parameters.

Thus, on the surface of the ground, the variability of the divergence of the radiation is very high. But as one rises in altitude, outside of cloud systems, this diminishes. The variability of the flux diminishes also when one increases the size of the integration surface. Therefore, it is at the top of the atmosphere where observation of the radiation field below it requires the least effort. This is because the flux densities E_{si} , E_{sr} and E_{ir} have the least variation. In order to observe them in a representative manner, one has to refer to the Shannon theorem and to know the required optimum sampling rate.

Unfortunately, the objective response cannot be based on the measurement of the variability of the quantities to be sampled, which up to the present have always been under-sampled.

This is the famous problem of sampling.

5. OBSERVATION OF RADIOMETRIC QUANTITIES ON THE GROUND

At a certain number of stations one observes the energy illumination $e_i = e_{si} + e_{ir\downarrow}^*$ and the global solar radiation e_{si} which is incident on a horizontal surface as well as the reflected radiation e_{sr} and the radiation balance e . Then one can calculate the albedo a . These measurements are usually made about 2 m above a grass surface. In spite of additional complications, one could ask whether one should not recommend a much higher altitude by imposing an average albedo which is typical for the region under consideration.

* $e_{ir\downarrow}$ is the descending infrared flux.

In any case, these difficult measurements are made with various instruments which are usually not comparable, and which give results which are highly sensitive to the atmospheric conditions.

The same is true for radiometric measurements carried out on a sounding balloon, and their significance can be problematical. Finally, observations made from aircraft have to be done more systematically on order to be correlated with the nature of the ground.

The observation of the direct solar radiation from the ground or from a site at a high altitude is of interest when it is associated with spectral measurements which determine the variability of the atmosphere transmission, assuming that the direct solar flux is constant.

Attempting to determine the solar constant from such measurements is at least hazardous, because very often, the atmospheric transmission is not known either.

6. OBSERVATION OF RADIOMETRIC QUANTITIES FROM SPACE VEHICLES

6.1 Radiometer with a hemispherical opening field

The difficulties are slightly different from those encountered on the ground because the satellite travels at an altitude which is much higher than one we are interested in. The problem is then to carry out measurements whose significance can be related to those in which we are interested.

On a planetary scale, let us assume that we wish to observe the space-time variation of the radiation balance, of the albedo, the incoming radiation and the departing radiation. In this case, we will observe the following:

- a) The direct solar radiation as a function of time in order to derive the value of the solar constant and its possible variations.
- b) The reflected solar radiation E_{ir} as well as the departing radiation ($E_{sr} + E_{ir}$) or the direct radiation E_{ir} , which could be possibly derived from the two preceding measurements.

Since in the absence of the atmosphere there are neither absorption sources nor sinks, we would have the following at a given time:

$$\int_{S_{hs}} E(l, g, t, h_s) ds = \int_{S_h} E(l, g, t, h) ds$$

for an integration which extends over the entire sphere as long as the altitude h_s of the instrument is greater than the altitude h of the atmosphere.

In principle, this does not mean one can go from the flux $E(l, g, t, hs)$ measured at the altitude h_s to the flux $E(l, g, t, h)$ at altitude h or vice versa. In effect, the extent of the radiation field observed at the altitude h_s is greater than the extent observed at the altitude h . The weighting of the sources is different because the source distribution is not known and is isotropic within the solar spectrum domain.

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It follows that observations designed to being integrated over the entire planetary sphere are necessary and have to be carried out at the same altitude.

In the same way as at ground level, the evolution of the planetary climate will be observed from the integral with respect to the net planetary flux time

$$\frac{1}{t_2 - t_1} \int_{t_1}^{t_2} \int_{S_{hs}} E(l, g, t, h_s) ds$$

The problem which then poses itself is to obtain at the instant t a sufficient number of measurements of E_{ir} and E_{sr} which are judiciously distributed over the sphere so that the fields of the reflected radiation and the departing radiation can be obtained in a representative manner so that they can be correctly described.

Therefore, one would wish to know the time interval Δt which is available in order to carry out measurements without having the radiation fields changed in an appreciable manner.

Finally, it is necessary to know the frequency for repeating the observation of the total planetary balance in order to have a high fidelity time integration with an accuracy which is coherent with the accuracy of the measurement instruments.

It is understood that the instantaneous representation or the integrated representation over time intervals which are increasing, of distribution maps of departing and reflected radiation fields, of the radiation balance and of the albedo from measurements carried out at a constant altitude, are very interesting in order to evaluate the space-time evolution of sources and sinks of radiation which affect the climate.

If at the same time the information could be determined from measurements performed at a lower altitude, one would then know how the space variability is attenuated as a function of observation altitude, and one might also determine a reduction algorithm.

For the infrared radiation E_{ir} , the reduction is not a problem because on the average the angular distribution of the emitted radiation does not depend on azimuth. Therefore, we can calculate

$$E_{ir}(h) = E_{ir}(h_s) \cdot \left(\frac{R + h_s}{R + h}\right)^2$$

where R is the radius of the Earth, h_s is the observation altitude and h is the required altitude.

Unfortunately, this cannot be done for the reflected solar radiation E_{sr} .

6.2 Scanning radiometer, proposition of a concept

The problem of the anisotropy of the distribution of the reflected solar radiation cannot be attacked unless one uses detectors having a high point space resolution on the source (reflected surface) along various incident angles.

Considered from this point of view, the optimum scanning methods for a scanning radiometer, which is a function of the objectives to be discussed below, would have to include signals collected for a particular collection of incidence angles coming from a defined point of the surface above the volume which one wishes to observe (troposphere). It then is apparent that the scanning would have to be organized so that end parallel lines shifted "on the ground" by a distance d . This is done so that the projection of the distance traversed by the satellite during a complete sweep, dead time and return time of the bundle would also correspond to d . The angle between each swept plane would, therefore, not be constant and the scanning configuration, velocity, distance d , dead time, would all depend on the satellite altitude. Also, it would be very desirable that from one orbit to the next, the scanning is retrograde, either using a remote command or this can be done automatically, so that the scanned traces "on the ground" would superimpose on one another, as well as in areas from which the radiation is reemitted.

If the measurements are sampled along each track, it would then be necessary to synchronize the measurement recordings. Finally, the resolutions "on the ground" of the observation bundle

at the ground track of the satellite would have to be selected so that they would be consistent with the accuracy instability with which a given point is observed under various incidence angles. Among other things, it would depend on the signal modulation frequency and the number of directions to be observed during a complete scan.

The scanning method proposed would allow one to obtain over a few orbits the maximum of information which would be directly usable for each point which had been observed while guaranteeing that the optical conditions are sufficiently constant.

Therefore, there arises the necessity of developing a statistic on the variability of the conditions which can prevail at the observed points, and this can differ widely.

The solution which we propose, its "philosophy" differs substantially from the method considered in the final report of the phase A study of the scanning radiometer planned for the European SEOCS project as well as the one planned for the American ERBS project.

It is obvious that one would install various filter spectral channels on a scanning radiometer. Let us remember that the quantitative interpretation of the measurements is a delicate matter due to calibration which depends on the spectral distribution of the source. This amounts to a great deal of difficulty.

6.3 Average space field radiometer

The reason why the use of an average space field radiometer is interesting is because one can determine "a weighted flux" for the instrument opening angle, which only comes from the extended source being observed in the direction of observation.

In order for the measurement type to be usable, the weighting of the flux within the opening cone of the instrument must only depend on the Lambert law, and must be independent of the luminescence distribution of the source. All of the detector points, therefore, must see the points of the entire surface of the source in the same manner. The amount of measurements to be processed could be considerably compressed and this is related to a scanning system described below. The integration of such a radiometer of very particular design within an observation system consisting of various satellites and instrument types will in general be difficult to evaluate if the geometries are not standardized so that measurements become comparable at the system level.

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7. OUR PRESENT KNOWLEDGE ABOUT THE RADIATION BALANCE

Measurements on the ground: At certain stations, the incident global solar radiation and the reflected one are measured systematically, but this is not true for the infrared component.

Also, the number of the stations is not only very small, but they are all made from ground stations with the exception of possible measurements made by oceanographic ships. At the present time, it is absolutely impossible to determine the ground radiation balance in a useful manner, in any other way but a microscale.

Measurements from satellites: Up to the present time, they are based on observations made from a satellite which is on a synchronous orbit. Any location overflown is observed every 12 hours. This means that one not only obtains truncated information, but the information is highly polarized and can only give an unreal image of the real phenomena.

Also, the large field instruments which have a high and average space resolution, allow one to qualitatively explore the radiation fields under consideration. However, one cannot obtain

quantitative well defined, homogeneous information, which can be compared between instruments and satellites.

In addition, it is obvious that the reconstruction of the departing radiation flux from an area corresponding to the synoptic scale, for example, on the surface above the troposphere, in principle, will give as a result the reflection of the collection of hypotheses which have to be made in the models for describing the situation. This is done from high resolution measurements usually made in a single direction and usually in two or three spectral bands.

The rather pesimistic evaluation of the present situation about the radiation leaving the atmosphere may also shed some light on the incoming radiation determined from the solar constant.

The most likely value of the solar constant evaluated on the basis of measurements made between 1960 and 1975 and corrected for the systematic error of the IPS 1958 scale gave $366.7 + 5.3 \text{ W.m}^{-2}$ for a confidence interval of 0.95.

If in addition one also considers the measurements performed by Hickey for the satellites NIMBUS 6, we find $1 371.0 + 4.8 \text{ W.m}^{-2}$ (the measurement made with the 3S detector on ERB was probably too high).

These values agree well with the measurements obtained by J. M. Kendall and R. C. Willson using absolute radiometers installed on rockets launched in 1976 and 1978. The observation duration was on the order of five minutes.

They found the following (private communication, TMQ December of 1978)

| | J. M. KENDALL | R.C. WILLSON |
|------|--------------------------|----------------------------|
| 1976 | $1 364 \text{ W.m}^{-2}$ | $1 371 \text{ W.m}^{-2}$ |
| 1978 | $1 368 \text{ W.m}^{-2}$ | $1 373,4 \text{ W.m}^{-2}$ |

During the flight of SPACELAB 1, independent observations will be performed by R. C. Willson and D. Crommelynck directly using absolute radiometers, but this time for 10 consecutive hours.

These measurements will be made simultaneously with those of G. Thuillier who will observe the distribution of the solar spectrum.

8. CONCLUSIONS

For the entire problem under consideration, it is finally the determination of the solar constant which will be answered soon. First of all, this is due to recent metrological developments in absolute radiometry and also because the Sun is a source which is simple to observe once one is outside of the atmosphere.

The other terms of the radiation balance could only be determined after a concerted action on an international scale is established. This is also true for the ground radiation balance.

We believe that one will finally begin to attack the problem of the atmospheric energy balance. The HERACLIDE project is an indispensable link for this but the difficulties are substantial.

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