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RADIATION MEASUREMENTS FROM POLAR AND GEOSYNCHRONOUS SATELLITES

T.H. VONDER HAAR, PRINCIPAL INVESTIGATOR

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ANNUAL REPORT
GRANT NGR-06-002-102
(PERIOD: 1 October 1972 - 30 September 1973)

DEPARTMENT OF ATMOSPHERIC SCIENCE
COLORADO STATE UNIVERSITY
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Radiation Measurements from Polar and Geosynchronous Satellites.

Annual Report

for

National Aeronautics and Space Adminstration
Grant NGR-06-002-102
(Period: 1 October 1972 - 30 September 1973)

by

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February, 1974

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SUMMARY

Emphasis during this third year of grant sponsorship has continued to be on utilization of satellite radiation budget data collected in the 1960's to many timely problems in atmospheric science. We have, however, begun to examine more recent data in the microwave channels. Our areas of application continue to be primarily:

a) Long-range weather (short term climate) forecasting and climate change monitoring;

b) The earth's environment as seen from space; the partitioning of energy transport between ocean and atmosphere; resolving observations of the earth's environment into contributions by land, ocean, clouds, and cloud free atmosphere; and

c) The Global Atmospheric Research Program (GARP), primarily through the radiation sub program of the GARP Atmospheric Tropical Experiment (GATE); for determining solar energy absorption in the atmosphere and ocean separately.

This has been a period for much scientific interaction on problems confronting the natural sciences. Better measurements of the earth's radiation budget for climate monitoring and application of existing satellite radiation budget data are germaine to the short and long term climate problem.

The Grant research has produced an exceptional number of reports and publications that have been very well received by the atmospheric science and space science community. Some results are being used to plan the next generation of radiation budget measuring systems and others have provided a foundation for analysis and study, often involving the use of other satellite data pertaining to clouds and earth surface features.

1.0 INTRODUCTION

The October 1972 to September 1973 period was a period for continuation and refinement of studies initiated during previous reporting periods. Efforts have been directed toward problems of the very short term (day-to-day) to the longer term (year-to-year and global climate).

Earlier Grant research supported the completion of two M.S. theses and at present two students are being supported by this grant, an M.S. candidate (S. Kidder) and a Ph.d. candidate (J. Ellis). Four papers published during this reporting period along with details not included in the body of this report appear in the appendices. Also included in the appendices is a cumulative summary of all reports and publications produced under this grant.

2.0 DISCUSSION OF SCIENTIFIC RESULTS

a) Minimum Albedo Study

We reported in the semi-annual report on minimum albedoes over land areas derived from Nimbus-3 measurements. Maps of minimum albedo have been completed for all ten semi-monthly periods of the Nimbus-3 data set. In snow free regions, these maps are free of over 80% of the cloud effects. Concurrent infrared measurements will permit the removal of still more clouds. Algorithms will be used to account for atmospheric optical properties and residual sub resolution cloudiness so that the earth's surface albedo and its variation with season can be resolved.

Knowledge of the earth's surface albedo and its variation in time will aid us in partitioning the radiative energy between that absorbed in the atmosphere and that absorbed at the earth's surface. We may then proceed with atmospheric energetic computations in studies and climate models with improved boundary conditions.

A zonally averaged profile for the annual minimum albedo (Figure 1) has been computed from the semi monthly data sets by taking those sets most representative in time for each season. This profile was requested and sent to Dr. Murray Mitchell of NOAA-EDS. Zonal profiles of this type are useful in zonal symmetric climate models.

Three regional maps of minimum albedo are included here as an example of what has been done and for some qualitative comparison. Figures 2 and 3 show the distribution over the North American Continent for April 15-30, 1969 and June 16-30, 1969, respectively; note the snowy areas with high albedo in the northern part of the continent during April; the opening of Hudson Bay in June; and small differences in the middle to southern part of the continent probably due to residual cloudiness, vegetation, and directional reflectance changes with season. Figure 4 shows the minimum albedo distribution over the African continent for the period June 16-30, 1969; the bright desert area of the north contrasts to the darker tropical regions in the central part of the continent.

b) Interannual Variability of the Radiation Budget

Work in the interannual variation radiation budget alone has not culminated in to any new publications during this reporting period. However, work has been progressing well; some new results and verification of earlier results will be forthcoming.

On the interannual variability of the net radiation budget and the general circulation of the atmosphere,(reported by Vonder Haar and Ellis, 1973) we have normalized some of the satellite data to account for various satellite heights and, thus, resolution of the data. Even with this refinement, the results continue to show a relationship between the radiation budget gradient "forcing" and the year-to-year changes in climate.

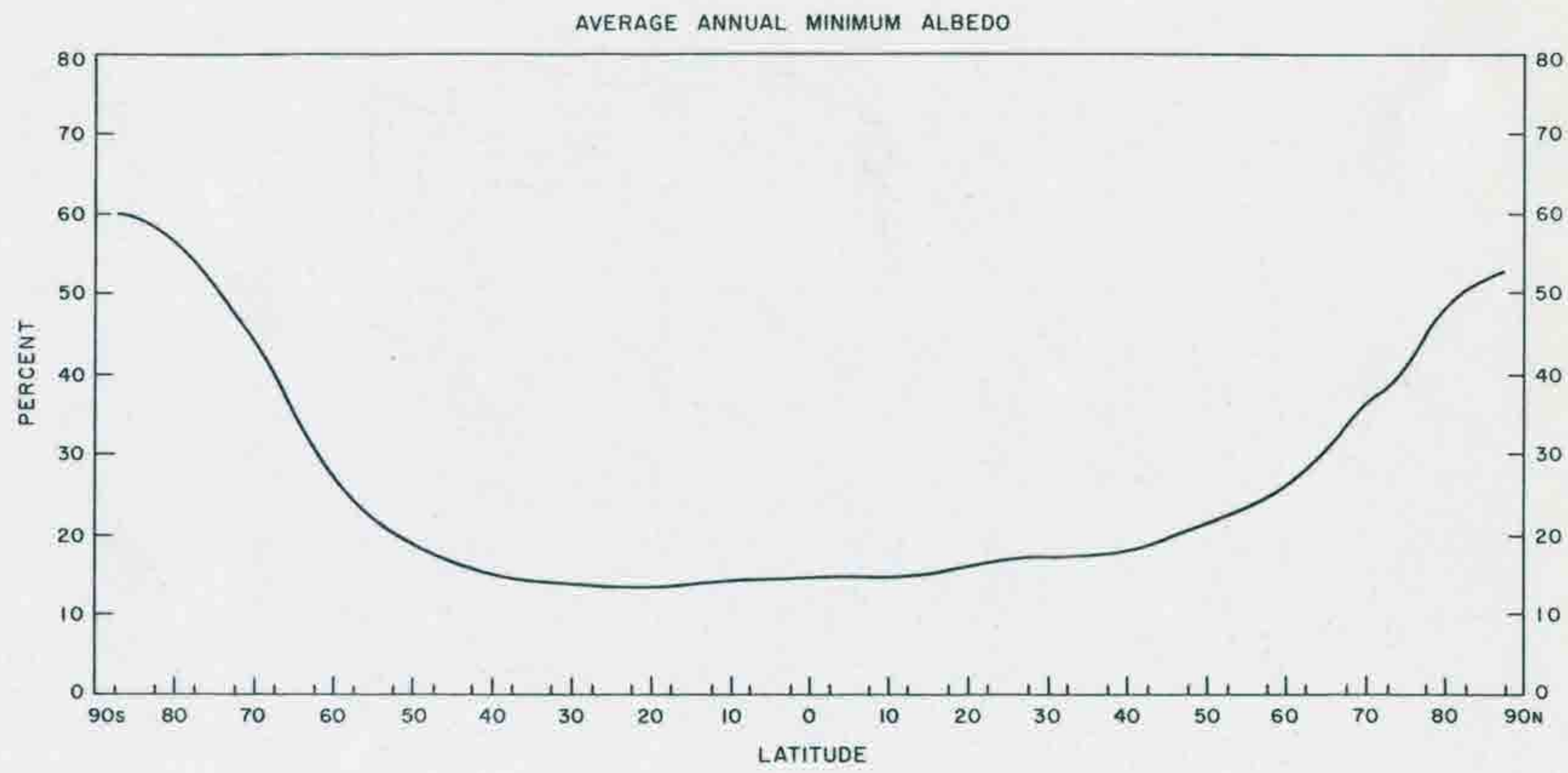

Figure 1: Zonal profile from Nimbus-3 MRIR measurements: April 1-15, July 16-31, October 3-17,1969; and January 21-February 3, 1970.

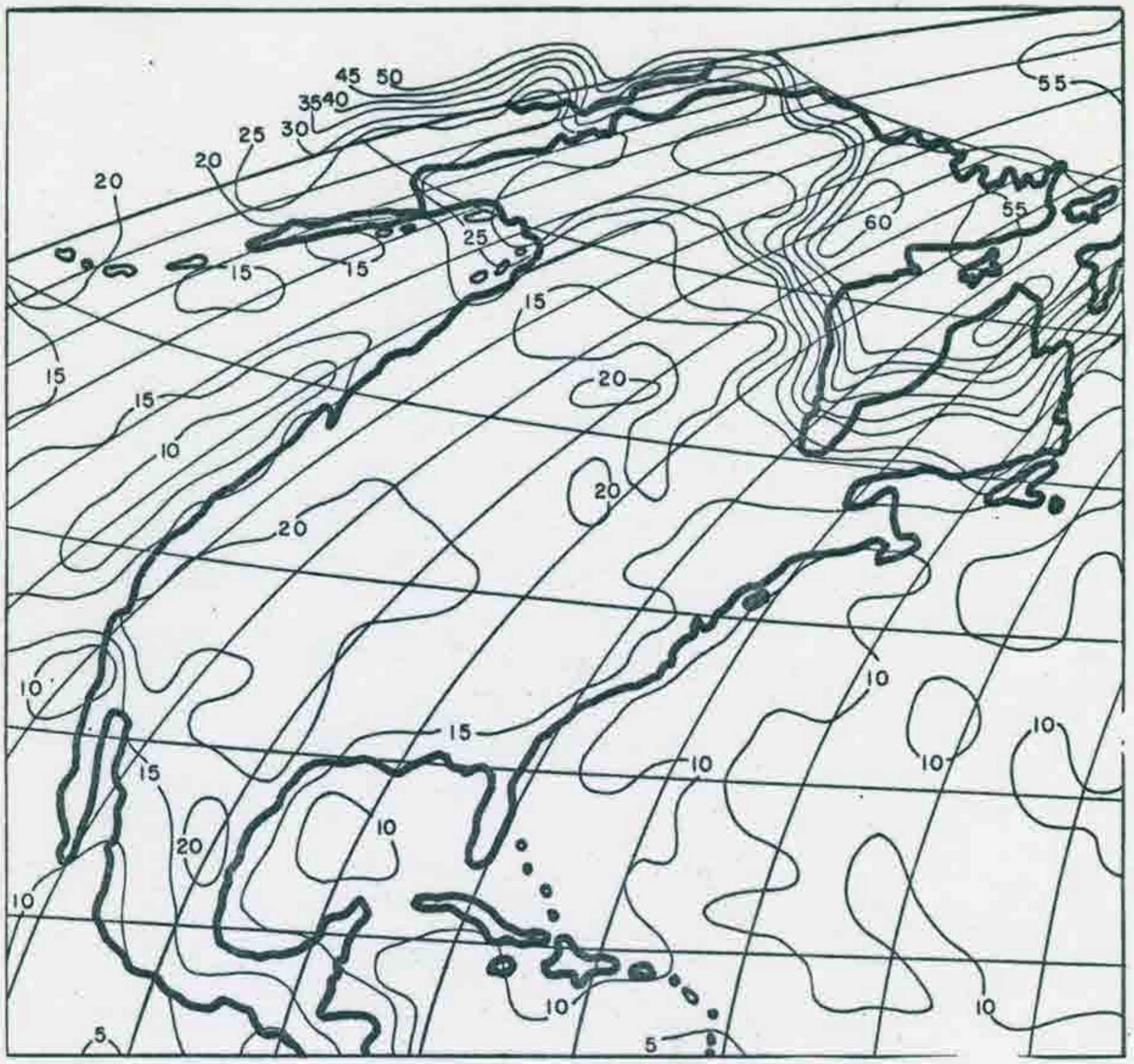

Figure 3: Minimum Albedo over North America from Nimbus-3 MRIR, April 15-30, 1969.

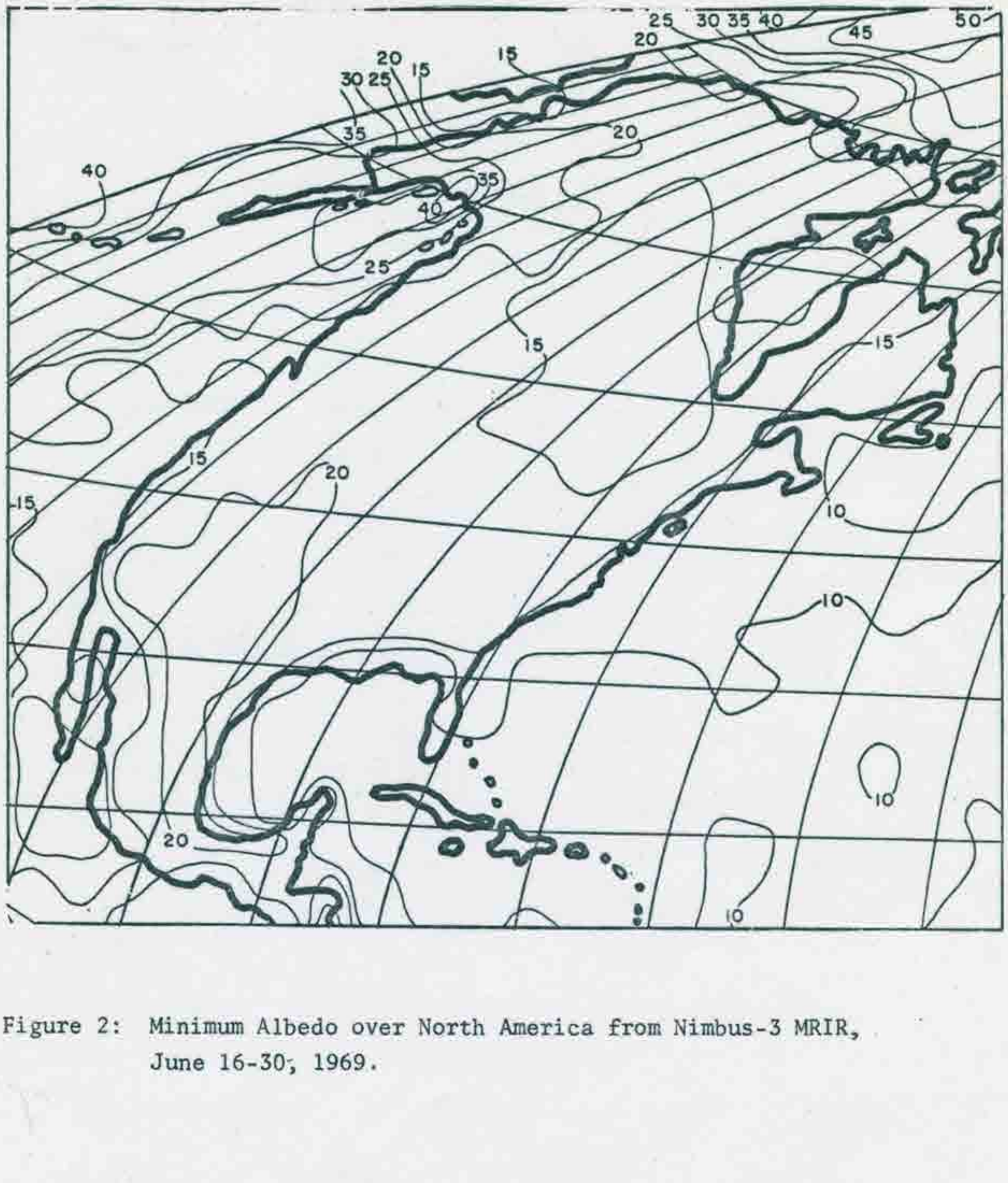

Figure 2: Minimum Albedo over North America from Nimbus-3 MRIR, June 16-30, 1969.

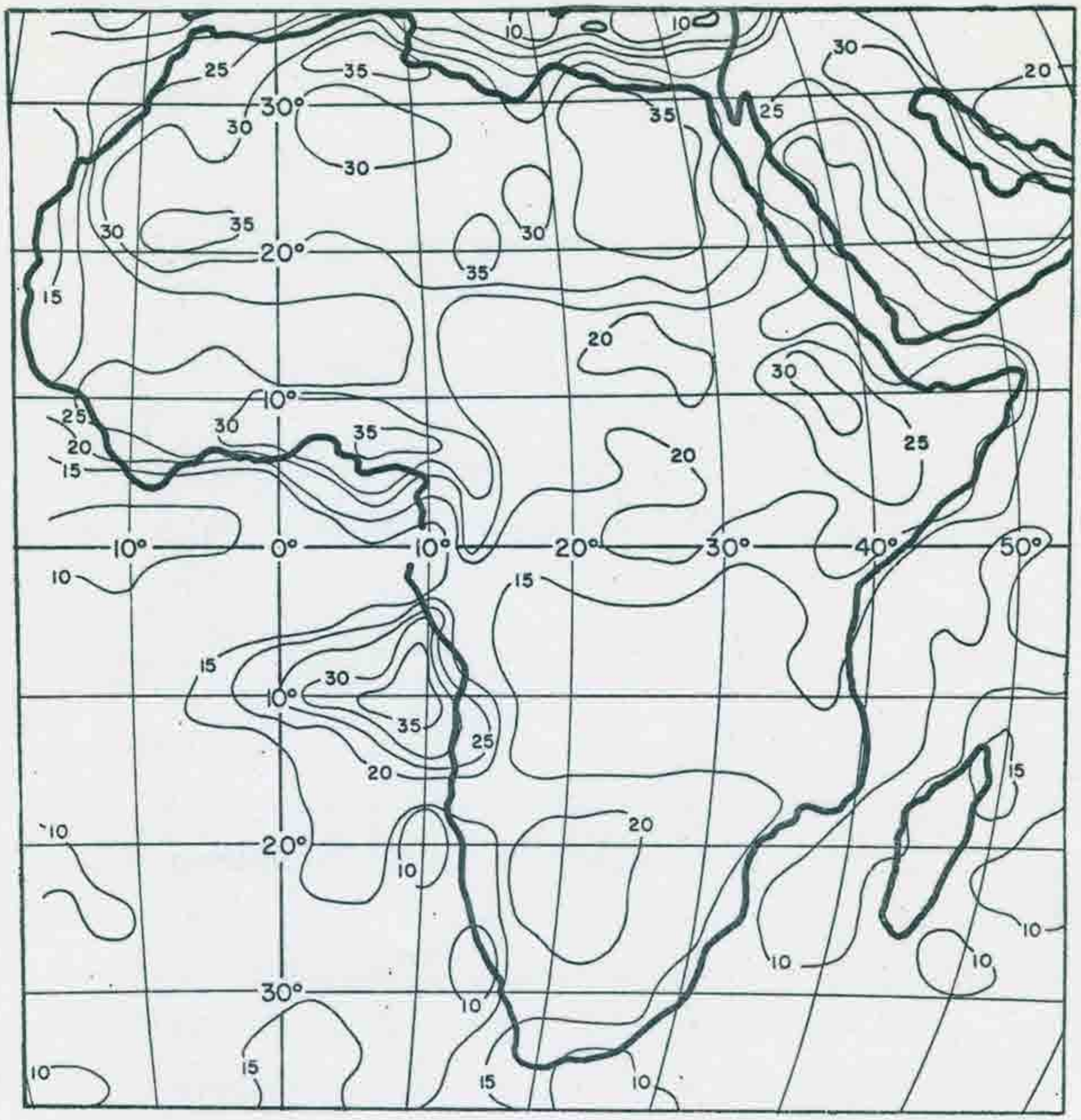

Figure 4: Minimum Albedo over Africa from Nimbus-3 MRIR, June 16-30,1969.

We are presently investigating the physical bases of this relationships by using, initially, zonal symmetric climate models. As this work progresses we may apply more sophisticated climate models to test results from this initial modeling effort.

We believe that once the physical basis for the interannual relationships are understood, then we will have a tool ready for application to the short term climate prediction problem.

c) Latent Energy Study

During the reporting period we began looking at Nimbus-5 ESMR data. Data have been mapped with latitude-longitude grid overlay. Investigations continue in the calibration between rainfall rate and brightness temperature.

d) Discussion of Recently Published Results[1]

Three papers dealing with the measurements of the radiation budget from the Nimbus-3 satellite were recently published (Appendix B). The first, NASA Technical Note D-7249, discusses the complete radiation budget experiment using data from the Medium Resolution Infrared Radiometer (MRIR), the extensive data reduction method (including assumptions) and results for four semi-monthly measurement periods (May 1-15, 1969; July 16-31, 1969; October 3-17,1969; and January 21- February 3, 1970). The semi-monthly period data were processed on the GSFC computer.

A second paper, published in the Journal of Atmospheric Science, analyzes the Nimbus-3 results in the form of annual averages. The annual maps and results were derived from data tapes at Colorado State University.

The Nimbus-3 radiation budget measurements and their analysis will

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[1]Reprints (except for the NASA Technical Note) are attached.

permit many scientific studies and results. Some of the first are noted in this report. A third paper, a German publication, gives a synopsis of the radiation budget measurements and analysis from U.S. satellites during the 1960's.

A paper published in the Journal of Physical Oceanography deals with a new determination of the energy that must be moved poleward by oceans in the Northern Hemisphere. Availability of satellite radiation budget data made this new estimate possible. This may very well be one way that we "monitor" our oceans in the years to come.

A number of papers were presented at various conferences during the reporting period. A summary of them appears in appendix A in a cumulative listing of papers and reports sponsored by Grant NGR-06-002-102.

The author served as chairman of the Informal Working Meeting for the GATE Radiation Sub-Programme, World Meteorological Organization, Leningrad, and is presently chairman of the GATE Radiation Working Group. The author has also served as a member of the NASA Science Team for Longterm Zonal Earth Radiation Budget Experiment, AAFE and as a member of the Science and Analysis Team for the Earth Radiation Budget Experiment on the Nimbus-G satellite.

3.0 PROGRAM FOR THE NEXT REPORTING PERIOD

A proposal for an extension of grant research was accepted by NASA in September 1973 for the period through September 1974; it contains detailed recommendation for future research.

Appendix A:

Cummulative Summary of Reports and Papers Under Grant NGR-06-002-102

1. A preliminary report on heat budget measurements from Nimbus-III was partly supported by this grant. It was presented at the XIIIth Meeting of COSPAR, Leningrad, 1970, and was published in Space Research XI (Springer-Verlag) as:

   The radiation balance of the earth-atmosphere during June and July 1969 from NIMBUS-III radiation measurements--some preliminary results

   by

   E. Raschke, T. Vonder Haar, W. Bandeen, and M. Pasternak

2. The very early results of four seasons of Nimbus radiation data were compared to earlier results from other satellites, with METEOR data obtained during the same time period and with calculations in a paper presented at the January 1971 Annual Meeting of the American Meteorological Society:

   Global measurements of the energy exchange between earth and space during the 1960's, including latest results from the NIMBUS-III satellite

   by

   T. Vonder Haar, E. Raschke, M. Pasternak, and W. Bandeen

   Publication of these comparisons awaited analysis of a more complete Nimbus data set (see #7).

3. In March 1971 the author presented an invited paper at the Miami Remote Sensing Workshop:

   Global radiation budget and cloud cover by satellite measurements

   by

   T. Vonder Haar

In addition, he served as discussion leader of a section that considered present opportunities and future possibilities for parameterizing the atmospheric energy budget using satellite data. Proceedings of this workshop will be published.

4. An invited paper was presented at the International Solar Energy Society Conference, NASA, GSFC, in May, 1971. This paper presents results of special interest to scientists concerned with the measurements and use of solar radiation. It was published in Solar Energy Volume 14, no. 2, 1972.

   Measurements of solar energy reflected by the earth and atmosphere, from meteorological satellites

   by

   T. Vonder Haar, E. Raschke, W. Bandeen and M. Pasternak

5. At the XIVth meeting of COSPAR (Seattle, 1971), in an open meeting of Working Group 6, we formally presented the annual results of the earth's radiation budget measurements from NIMBUS-III. They independently confirmed global results obtained from earlier satellites, while providing the first high area resolution view of energy exchange between earth and space on the annual scale. The paper, was published in Space Research Vol. 12, 1972 and is entitled:

   The radiation budget of the earth-atmosphere system as measured from the NIMBUS-III satellite (1969-70)

   by

   T. Vonder Haar, E. Raschke, M. Pasternak and W. Bandeen

6. Drs. Budyko and Flohn kindly invited a paper on the NIMBUS-III results for their Symposium on Physical and Dynamical Climatology, Leningrad, August 1971. The paper, read in the authors absence by Dr. A. Drummond will be published in the symposium proceedings. It was titled:

Climatological studies of the earth's radiation budget and its variability with measurements of the satellite NIMBUS-III

by

E. Raschke and T. Vonder Haar

7. An invited paper at the Joint Meeting of the German Physical and Meteorological Societies, Essen, October 1971 contained a discussion of the new NIMBUS results within the framework of the earlier satellite measurements, especially with regard to interannual variations. It was published in a German journal, Amalen Meteor, 6 - No. 711, 1973.

Measurements of the energy exchange between earth and space during the 1969's from satellites

by

T. Vonder Haar and E. Raschke

8. In addition to the formal papers and publications, one of the most personally satisfying events of the reporting period was a 90-minute seminar presented in early November 1971 in the invited seminar series of the Geophysical Fluid Dynamics Laboratory, NOAA/Princeton University. Entitled: Measurements of the Earth's radiation budget from satellites: Status, prospects and relation to atmospheric energetics, the seminar reiterated both the wide-ranging relevance of radiation budget data to many atmospheric problems as well as the interest of other scientists in these data. This same experience has greeted the author during similar seminars presented in recent years at MIT, NYU, University of Colorado, and Colorado State University.

9. Invited paper at the International Radiation Symposium, Sendai, Japan, May - June 1972 and also presented at the Conference on Atmospheric Radiation, Fort Collins, Colorado, August 1972. Paper discusses variations in the Radiation Budget as measured by satellites at various

spatial and temporal scales i.e. spatial scales: global, hemispherical, zonal, regional, ocean-land; and time scales: hourly, daily, monthly, and yearly.

<u>Natural variation of the radiation budget of the earth-atmosphere system as measured from satellites</u>

by

T. Vonder Haar

10. A paper was presented at the Conference on Atmospheric Radiation, Fort Collins, Colorado, August 1972 which discusses an experiment to measure the radiation budget at the surface over a snow field and its variation with changing solar Zenith angles and cloudiness. This information is needed to understand the total heat budget of polar areas which is vital to understanding our climate changes.

<u>The albedo of snow in relation to sun position</u>

by

H. Korff and T. Vonder Haar

11. Measurements of the earth's radiation budget from satellites were combined with atmospheric energy transport summaries to show the required transport by the oceans between equator to pole. The results show that the ocean must transport more energy than previously believed, a timely result, since there is a renewed interest in the influence of the ocean on weather and climate. Published <u>Journal of Physical Oceanography</u> April 1973.

<u>New estimate of annual poleward energy transport by Northern Hemisphere oceans</u>

by

T. Vonder Haar and A. Oort

12. The frequency and occurance of opaque cloudiness were determined from satellite brightness data. Opaque cloudiness interferes with remote sensing of the vertical temperature profile of the atmosphere. The study indicated regions of the globe where remote temperature sounding at spectral regions less than microwave bands are not feasible due to persistent opaque cloudiness - necessary information for the Global Atmospheric Research Program (GARP) planning.

A study of extreme and persistent cloudiness based on satellite observations (1969-1970)

by

P. Downey, S. Lassman, and T. Vonder Haar

13. Nimbus III MRIR data were combined with surface albedo and actinometric measurements to determine the temporal (15 day to year) and spatial (regional to global) distribution of atmospheric absorption of solar energy. In addition a statistical parameterization relating atmospheric absorption to precipitable water, opaque cloud cover, and satellite measured albedo was developed.

Distribution and parameterization of absorption of solar radiation in the atmosphere

by

P. Downey (M.S. thesis)

14. Satellite measurements of the earth-atmosphere radiation budget components, comprising 36 monthly data sets, were used to compute the north-to-south net radiation gradient - the forcing function for the large scale atmospheric and oceanic circulation. These data, when compared to atmospheric circulation parameters, indicate that year-to-year anomalies in the large scale atmospheric circulation lag the year to year anomalies in the gradient of net radiation by 3 to 6 months.

Interannual variations in the earth's radiative budget and the general circulation

by

J. Ellis, (M.S. Thesis)

15. Invited paper presented to a joint session of the Radiometry and Photometry and Atmospheric Optics Technical Groups, 1973 Meeting of the Optical Society of America, Denver, Colorado discussed the precision and accuracy required of radiometric measurements by satellites at various time and space scales-particularily, the global climate change and its measurement problems.

Global heat balance

by

T. Vonder Haar

16. Invited paper at the 1973 National Center for Atmospheric Research (NCAR) Summer Climate Meeting, Boulder, Colorado, a national collection of scientists involved in climate research. The capability for measurements from satellites of the initial and boundary conditions for inclusion into global climate models was assessed. Satellite measurements to date show that the short term climate (year to decade) is not stagnant.

Satellite observations of the earth's energy budget

by

T. Vonder Haar

17. In a paper presented at the Interdisciplinary Symposium on the study of Snow and Ice Resources, Monterey, California, December 1973, the data reduction technique applied to Nimbus III measurements for albedo and the need for additional surface measurements of bidirectional

reflectance characteristics of ice and snow surfaces were discussed.

Measurement of albedo over polar snow and ice fields using Nimbus-3 satellite data.

by

T. Vonder Haar

18. Invited paper at the Smithsonian Symposium on Solar Radiation Measurement and Instrumentation, Rockville, Md., November 1973, in which results of measurements with different experiments of the solar energy reflected and scattered from the earth-atmosphere were presented. The application of these measurements to several environmental problems was reviewed and new experiments designed to obtain future albedo measurements were noted.

Measurement of the Planetary Albedo from Satellites

by

T. Vonder Haar

19. NASA Technical Note D-7249, April 1973, discusses the complete radiation budget experiment using data from the MRIR on Nimbus 3, the extensive data reduction method (including assumptions) and results for four semi-monthly measurements periods (May 1-15, 1969; July 16-31, 1969; October 3-17, 1969; and January 21 - February 3, 1970).

The radiation balance of the earth-atmosphere system from Nimbus-3 radiation measurements

by

E. Raschke, T. Vonder Haar, M. Pasternak, and W. Bandeen

20. Measurements of reflected solar radiation and emitted thermal radiation taken with the MRIR on Nimbus-3 satellite are presented for the 10 semi-monthly periods spanning April 1, 1969 to February 3, 1970. Results on the planetary albedo, the amount of absorbed solar radiation, the infrared radiation loss to space, and the radiation balance

of the earth-atmosphere system are discussed at various scales: global, hemispherical, and zonal averages as well annual polar and global maps.

<u>The annual radiation balance of the earth-atmosphere system during 1969-70 from Nimbus 3 measurements</u>.

by

E. Raschke, T. Vonder Haar, W. Bandeen, and M. Pasternak

APPENDIX B

Preprints of all publications of the reporting period except for NASA TN D-7249 for which the cover page and abstract only are enclosed.

NASA TECHNICAL NOTE

NASA TN D-7249

NASA TN D-7249

THE RADIATION BALANCE OF THE EARTH-ATMOSPHERE SYSTEM FROM NIMBUS 3 RADIATION MEASUREMENTS

by Ehrhard Raschke, Thomas H. Vonder Haar, Musa Pasternak, and William R. Bandeen

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Greenbelt, Md. 20771

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Goddard Space Flight Center Greenbelt, Maryland 20771	11. Contract or Grant No.
	13. Type of Report and Period Covered
12. Sponsoring Agency Name and Address	Technical Note
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15. Supplementary Notes

16. Abstract

The radiation balance of the Earth-atmosphere system and its components has been computed from global measurements of radiation reflected and emitted from the Earth to space. These measurements were made from the meteorological satellite Nimbus 3 during the periods from April 16 to August 15, 1969; October 3 to 17, 1969; and January 21 to February 3, 1970.

This report is primarily a discussion of the method of evaluation, its inherent assumptions and possible error sources. Results are presented by various methods: (1) global, hemispherical, and zonal averages obtained from measurements in all semimonthly periods and (2) global maps of the absorbed solar radiation, the albedo, the outgoing longwave radiation, and the radiation balance obtained from measurements during semimonthly periods in each season (May 1 to 15, July 16 to 31, and October 3 to 17, 1969, and January 21 to February 3, 1970).

Annual global averages of the albedo of 28.4 percent and of the outgoing longwave radiation of 0.345 cal cm^{-2} min^{-1} have been determined. These values balance to within 1 percent the annual global energy input by solar radiation that has been computed for a solar constant $S_0 = 1.95$ cal cm^{-2} min^{-1}.

17. Key Words (Selected by Author(s))	18. Distribution Statement
Albedo Energy budget of Earth MRIR Nimbus 3 Radiation	Unclassified–Unlimited

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The Annual Radiation Balance of the Earth-Atmosphere System During 1969–70 from Nimbus 3 Measurements

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(Manuscript received 12 October 1972, in revised form 15 January 1973)

ABSTRACT

Measurements of reflected solar radiation and emitted thermal radiation taken with a radiometer on the meteorological satellite Nimbus 3 during 10 semi-monthly periods (April–15 August, 3–17 October, 1969; 21 January–3 February, 1970) provided for the first time high-resolution data on the earth's annual global radiation budget. Results on the planetary albedo, the amount of absorbed solar radiation, the infrared radiation loss to space, and the radiation balance of the earth-atmosphere system are discussed at various scales: global, hemispherical, and zonal averages; as well as global and polar maps with a spatial resolution of about synoptic scale (10^2–10^3 km).

The incoming solar radiation (taking the most recent value of the solar constant $S_0 = 1.95$ cal cm^{-2} min^{-1}) is balanced within the accuracy of the measurements and evaluation procedure by a global albedo of 28.4% and an infrared heat loss to space of 0.345 cal cm^{-2} min^{-1}, which corresponds to a mean planetary effective radiation temperature of 255K. These results confirm those found from earlier satellite data, which showed that our planet is darker and radiatively warmer than previously assumed from estimates with climatic data. From zonal averages of the radiation balance the required poleward transport of energy was found to be larger over the Northern than over the Southern Hemisphere during the 1969–70 observational period.

1. Introduction

The radiation balance Q_N is the net radiant flux density at a fictitious horizontal element of area outside the atmosphere that is crossed by fluxes in incoming solar radiation and outgoing reflected solar and emitted thermal radiation. It is defined as

$$Q_N = W_S - W_R - W_E, \tag{1}$$

where at that area element W_S is the irradiance of solar electromagnetic radiation, and W_R and W_E are radiant flux densities reflected and emitted from the earth to space. The planetary albedo is determined by the ratio W_R/W_S.

Solar electromagnetic radiation reaching the earth's atmosphere is the principal energy source for the atmospheric-surface system since the solar particle flux, electromagnetic radiation from other stars, and the heat flux from the earth's interior are some orders of magnitude weaker. Part of the solar electromagnetic radiation is reflected and scattered back to space, primarily from clouds and other lower atmospheric constituents, while the rest is absorbed and heats the atmosphere, land surfaces, and the oceans. Also, clouds, aerosols and gases in the lower atmosphere, and to some lesser extent at the earth's surface, emit infrared radiation to space. Therefore, these discussions of the radiation balance of the earth-atmosphere system refer to the exchange of radiative energy between space and the earth-atmosphere system, *viz.* the earth's surface and the lower atmosphere up to about 50 km altitude.

The earth's radiation balance has been the subject of detailed scientific studies for many years, since its geographical distribution (heat gain at the equator and heat loss over both poles) is the key mechanism that forces our atmospheric circulation; it also is of fundamental importance to climate and weather. Detailed knowledge of it permits investigations of the poleward energy transport required to maintain the observed state of the earth-atmosphere system; estimates of the radiation budget at the surface and, thus, of the atmosphere and ground (oceans) separately; verifications of the energy budget of modern numerical circulation models at their upper boundary; and determinations of local and global climatic trends. Some preliminary re-

[1] These authors have made equal contributions to this paper.

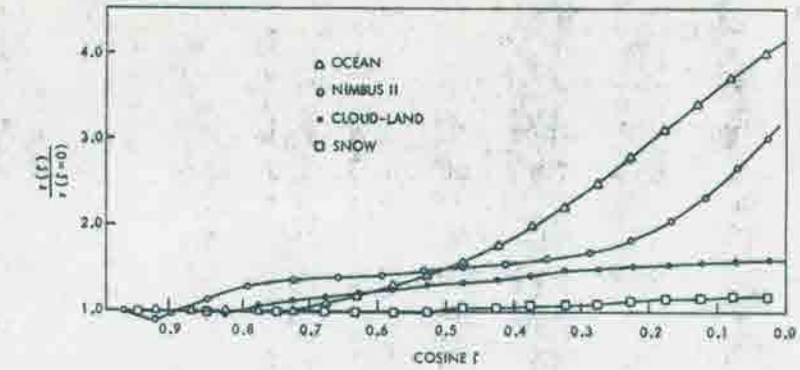

FIG. 1. Change of the directional reflectance $r(\zeta)$ with the sun's zenith angle ζ.

sults of such applications have already been reported in the literature (e.g., Fritz *et al.*, 1964; Hanson *et al.*, 1967; Holloway and Manabe, 1971).

The acquisition of such detailed knowledge will require, over periods of several years, precise and properly sampled measurements that are not available so far. The measurements of the meteorological satellite Nimbus 3, however, provide for the first time estimates of the annual radiation budget with a high spatial resolution over the entire globe. They were done in 10 semi-monthly periods during all seasons during the period from 16 April 1969 through 3 February 1970 with a stable and calibrated radiometer.

The evaluation methods and their possible error sources were described in a previous paper by the same authors (Raschke *et al.*, 1973). Some preliminary results from Nimbus 3 were presented by Raschke *et al.* (1971), Raschke and Vonder Haar (1971), Vonder Haar and Raschke (1972), and Vonder Haar *et al.* (1972) in earlier papers. The present paper provides the most extensive

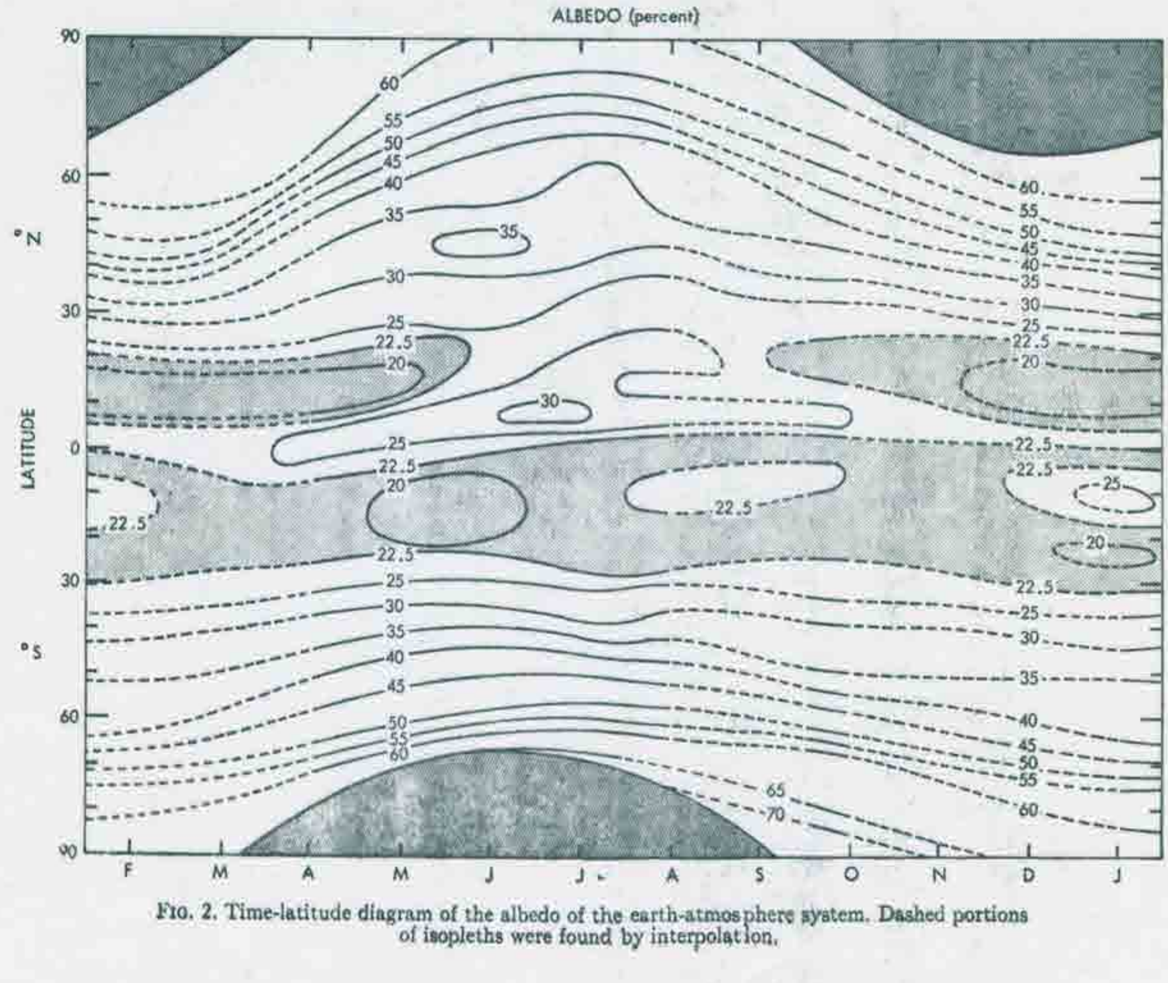

FIG. 2. Time-latitude diagram of the albedo of the earth-atmosphere system. Dashed portions of isopleths were found by interpolation.

TABLE 1. Global and hemispherical radiation budget (cal cm^{-2} min^{-1}) of the earth-atmosphere system (N=north, S=south, G=globe).

Period		Solar radiation Incoming	Solar radiation Absorbed	Albedo	Outgoing longwave radiation	Radiation balance
16–30 April 1969	N	.586	.410	.300	.349	+.061
	S	.379	.277	.270	.342	−.065
	G	.483	.344	.288	.346	−.002
1–15 May 1969	N	.618	.431	.302	.351	+.080
	S	.334	.244	.269	.343	−.099
	G	.476	.337	.291	.347	−.009
16–31 May 1969	N	.641	.440	.314	.355	+.085
	S	.310	.228	.264	.346	−.118
	G	.476	.334	.298	.350	−.016
1–15 June 1969	N	.656	.454	.308	.359	+.095
	S	.290	.213	.267	.343	−.130
	G	.473	.333	.296	.351	−.018
16–30 June 1969	N	.659	.462	.299	.362	+.100
	S	.283	.206	.271	.342	−.136
	G	.471	.334	.291	.352	−.018
1–15 July 1969	N	.652	.459	.296	.365	+.094
	S	.291	.213	.267	.344	−.131
	G	.471	.336	.286	.355	−.018
16–31 July 1969	N	.633	.449	.290	.363	+.086
	S	.311	.230	.261	.345	−.115
	G	.472	.339	.281	.354	−.019
1–15 Aug. 1969	N	.609	.434	.287	.365	+.069
	S	.340	.248	.271	.341	−.093
	G	.474	.341	.280	.353	−.012
3–17 Oct. 1969	N	.443	.323	.270	.351	−.028
	S	.541	.384	.291	.344	+.040
	G	.492	.353	.282	.348	+.006
21 Jan.–3 Feb. 1970	N	.343	.249	.273	.332	−.083
	S	.663	.473	.287	.342	+.131
	G	.501	.359	.283	.337	+.023
Annual*	N	.483	.344	.287	.346	−.002
	S	.492	.354	.280	.344	+.010
	G	.488	.349	.284	.345	+.004

* Estimated.

discussion of annual results obtained so far from the Nimbus 3 measurements.

2. Previous studies of the radiation budget

Many authors based their studies of the radiation budget on climatological data and relatively simple radiative transfer models (Dines, 1917; Simpson, 1929; Baur and Phillipps, 1934, 1937; Houghton, 1954, London, 1957; Gabites, 1959; Budyko, 1963; Gavrilova, 1963; Vinnikov, 1965; Fletcher, 1965; Katayama, 1967; London, and Sasamori, 1971; Kondratiev and Dyachenko, 1971) or of the albedo alone (Fritz, 1949). Danjon (1936) derived from a large variety of measurements of the earthshine on the moon a value for the planetary albedo which has been reevaluated later from the same measurements by several authors (e.g., Penndorf, 1937; Ångström, 1962). All of the theoretical studies, although done with care, were hampered in their accuracy due to the insufficiently available observational material and the various oversimplifying assumptions in their radiative transfer models. Since both the data base and radiation computation technique have shown steady improvement, the London and Sasamori calculations are state of the art. Nevertheless, it is now possible to measure the earth's radiation budget better than it can be calculated.

Danjon's observations, since they were done mostly from the territory of France, did not allow a proper sampling over all sunlit portions of the earth as visible from the moon during a period of several years. It was recognized many years ago that direct observations from satellites, if properly sampled (Godson, 1958; House, 1962) could overcome this problem (e.g., Suomi, 1958).

Weinstein and Suomi (1961) discussed the first measurements obtained with omnidirectional sensors from Explorer 7 in 1959. Other measurements with the afore-mentioned techniques and with flat-plate sensors were described in the following years by several authors (House, 1965; Vonder Haar, 1968; Vonder Haar and Suomi, 1971; McDonald, 1970). They provided only very low spatial resolution due to their observing geometry. Results on the annual and seasonal radiation budget have been obtained with proper assembling of this large variety of data by Vonder Haar (1968) and Vonder Haar and Suomi (1969, 1971). They showed that the earth has a warmer effective radiation temperature and is darker than previously assumed from theoretical studies and earthshine measurements. This was especially true in the tropics. Holloway and Manabe (1971) compared the radiation budget of their simulation model at its upper boundary with these earlier results and found good agreement considering the radiation parameterization employed within the model.

Other satellite measurements of the radiance in narrow fields of view allowed a much higher spatial resolution of the earth's radiation field ($\sim$200 km$\times$200 km). Results were discussed in various papers by Bandeen *et al.* (1965), Rasool and Prabhakara (1966), Winston and Taylor (1967), Boldyrev and Vetlov (1970), Raschke and Pasternak (1968), Raschke *et al.* (1968) and Raschke and Bandeen (1970). These latter two and other subsequent papers reported detailed studies of the radiation budget obtained with a calibrated scanning radiometer over a period of 2½ months in the middle of 1966. This instrument was onboard the satellite Nimbus 2. Global averages of the albedo and the outgoing longwave radiation derived from those measurements were similar to those reported by Vonder Haar (1968) from the other satellite measurements with hemispherical radiometers (e.g., the lower albedo in the tropics) and balanced within the probable accuracy of evaluation the incoming solar radiation. Similar measurements are now available during all seasons of one annual cycle from Nimbus 3. Their nature and evaluation are discussed in the two following sections of this paper.

The available satellite observations at present do not allow observation of climatic trends that might have occurred over various parts of the globe during the last decade, since they were done with various instrumental designs and primarily from only one satellite during a specific time period.

3. Nimbus 3 measurements

The satellite Nimbus 3 was launched on 14 April 1969, into a sun-synchronous circular polar orbit where it passed the equator northbound at about 1130 and southbound at 2330 local time at a mean orbital height of 1100 km.

These orbital parameters enabled the cross-track scanning, five-channel radiometer (McCulloch, 1969) to measure reflected solar radiation once and emitted thermal radiation at least twice a day over most areas of the earth. They did not, however, allow observations of a primary factor in the total outgoing radiation, *viz.* the diurnal variations of cloudiness over low-latitude regions. This radiometer provided continuous data during the four-month period between 16 April and 15 August, 1969. Malfunction of one of the tape recorders and the data flow from other experiments onboard Nimbus 3 allowed continuous recordings during only two additional, nearly semi-monthly periods, which were selected specifically to sample an entire annual cycle (3–17 October 1969 and 21 January–3 February, 1970).

One channel of this radiometer was sensitive, but not with an ideal filter curve, in the spectral interval between 0.2 and 4.8 μm, which covers completely the spectrum of solar radiation reflected and scattered from the earth back to space. The consistency of its measurements had been checked carefully with reflectance measurements over various cloud-free parts over the Libyan desert where no instrumental deterioration could be detected during the entire period of observation.

The accuracy of the other four channels sensitive in separate narrow bands in the infrared (6.3-μm band sensing upper tropospheric water vapor; surface radiation between 10–12 μm; 15-μm band of carbon dioxide; and emission of lower tropospheric water vapor and clouds between 20 and 23 μm) was checked continuously with onboard calibration systems. The experiment data had very high relative accuracy and no observable bias error. Random errors of measurements of about 1% were expected due to digitization errors. Absolute accuracy of the results was affected both by sensor detectivity and techniques of data processing described in the next sections.

Over most areas of the earth, measurements of the upward radiation were made daily from Nimbus 3. Small gaps occurred, in particular during the period 21 January–3 February, 1970, over North America and the adjacent Pacific Ocean (daytime measurements) and over the Atlantic Ocean along the western coastal areas of Europe and Africa.

4. Evaluation method

a. General outlines

Due to the orbital parameters and the narrow field of view of the instrument the primary purpose of the evaluation methods was to compute daily averages of the radiant *flux densities* of reflected solar and emitted thermal radiation from respective single measurements of the radiance over each area.

Daily averages of the radiant flux densities of reflected solar and emitted thermal radiation from each global area element were then computed from the measured "filtered" radiances by: 1) computation of the total radiance from the "filtered" measurements, 2) correction for dependence on zenith and azimuthal angle, 3) computation of the radiant densities at the

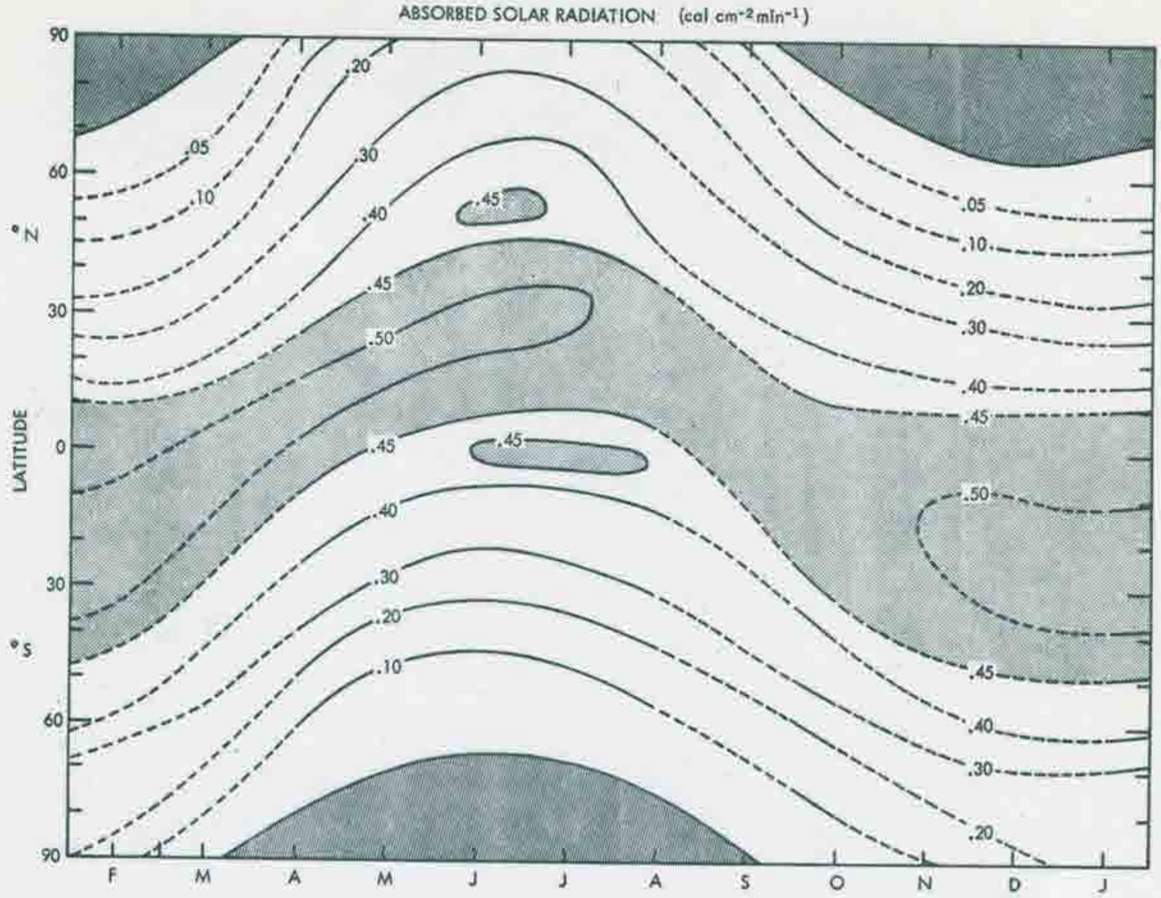

FIG. 3. Time-latitude diagram of the irradiance of solar radiation absorbed in the earth-atmosphere system. Dashed portions of isopleths were found by interpolation.

time of observation, and, 4) computation of the daily average over each area.

The results were assembled in Mercator maps with a mean spatial resolution of about 500 km×500 km in near-equatorial regions and in polar-stereographic maps with a spatial resolution of about 250 km×250 km per grid area.

This evaluation procedure was based on several generalized models which will be described briefly in the next two sections. They were essentially the same as applied previously to Nimbus 2 data (Raschke and Bandeen, 1970), although the newer reflectance models were slightly different. To avoid obstruction by clouds, all those measurements which were obtained at nadir angles >45° were omitted. Further, measurements of reflected solar radiation that were obtained over areas illuminated by a very low sun (solar zenith angle larger than 80°) were also omitted. The radiation balance results were grouped into semimonthly periods to average over variations of the radiation fields due to travelling disturbances.

b. Outgoing shortwave radiation

To compute the total (0.3–4.0 μm) flux density from the measured "filtered" radiance, N_f, it is assumed that the bidirectional reflectance ρ computed by use of (2) equals that of the total solar spectrum (Raschke *et al.*, 1973):

$$\rho(\lambda,\phi,t;\theta,\psi,\zeta)=\frac{N_f(\lambda,\phi,t;\theta,\psi,\zeta)}{S_f'L\cos\zeta(\lambda,\phi,t)}\,[\mathrm{sr}^{-1}], \qquad (2)$$

where ζ is the sun's zenith angle at the moment of measurement on day t of the year, and S_f' is the extraterrestrial "filtered" solar radiation obtained by weighting of Labs and Neckel's (1968) spectral irradiance data which were adjusted to a value of the solar constant of $S_0=1.95$ cal cm^{-2} min^{-1} (Drummond, 1970; Thekaekara, 1970) with the spectral response of the radiometer; L accounts for the deviation of the true earth-sun distance from one astronomical unit; θ and ψ are the zenith and azimuthal angle of measurement with respect to the principle plane, and the sun's zenith angle, respectively; while λ and ϕ are geographical longitude and latitude of an observed area.

The directional reflectance r, i.e., the ratio between the radiant flux density of reflected radiation and the irradiance of solar radiation, has been determined with corrections for anisotropic reflection properties of the earth-atmosphere system. Since, over most areas, the cross-track scan of the instrument and the satellite

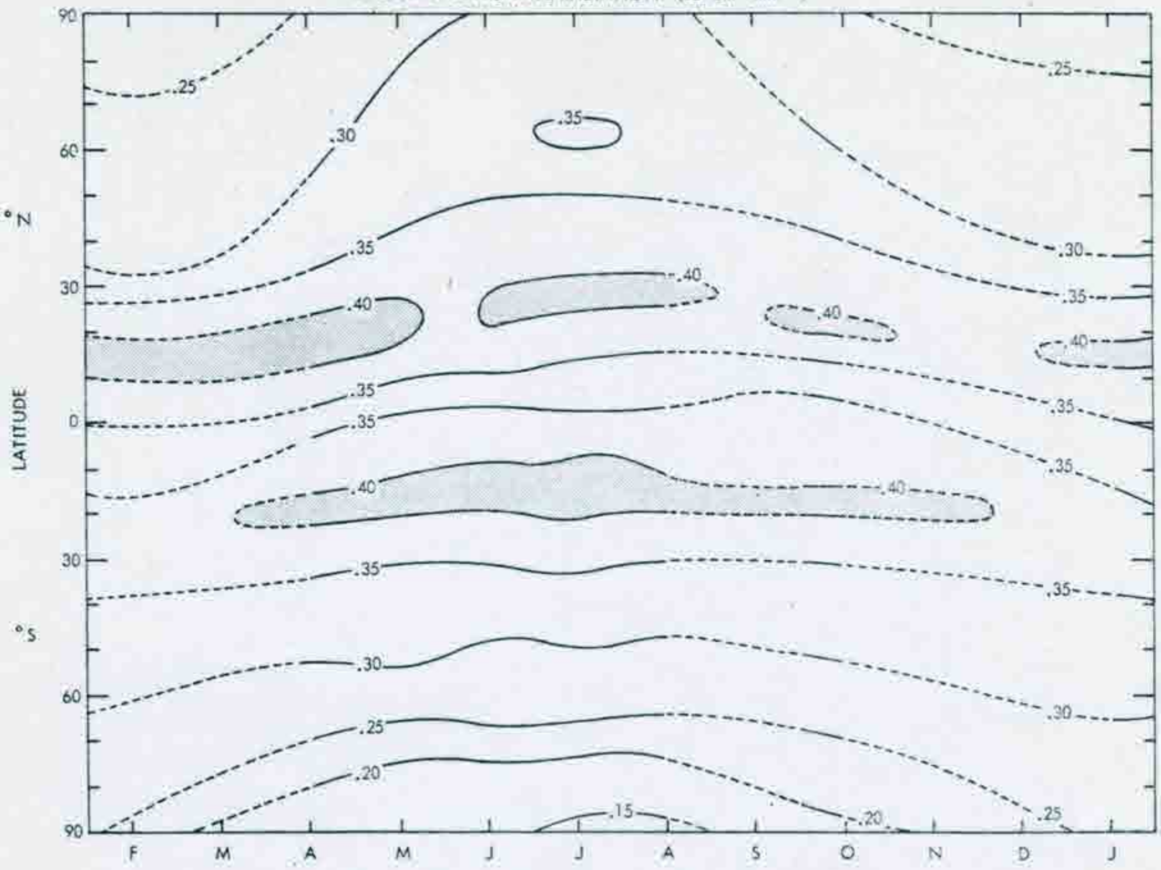

FIG. 4. Time-latitude diagram of the radiant emittance of longwave radiation emitted to space. Dashed portions of isopleths were found by interpolation.

orbit did not allow measurements of ρ over each area at various angles θ and ψ, only gross-empirical models could be used to relate ρ to r. These models were derived from published airplane, balloon and satellite measurements of reflected solar radiation. Nine models were developed for three different ranges of the sun's zenith angle (0–35°, 35–60°, 60–80°) and three types of observed surfaces representing high-latitude ice and snow fields (latitude>65° and $\pi\rho > 50\%$), cloud-free ocean areas ($\pi\rho < 10\%$) and effective blackbody temperature $T_e > 273$K for concurrent measurements in the 10–12 μm channel), and all other land and cloudy areas. The values in parentheses specify the conditions used to objectively assign each single satellite measurement to a specific model category.

The integration over the entire daylight period made use of three other models which account for the change of the directional reflectance r with the sun's zenith angle ζ, for different surface types. They were also obtained from observational material (see Raschke *et al.*, 1973). These relations are shown in Fig. 1, where for comparison the one used for the evaluation of Nimbus 2 data (Raschke and Bandeen, 1970) is also drawn. All show an increase of $r(\zeta)$ with increasing ζ, which is largest over cloud-free oceans (low albedo of the surface) and smallest over snow and ice fields. This latter curve has been obtained from gound observations published by Kondratiev (1969). Recent ground observations over snow at 3300 m altitude reported by Korff and Vonder Haar (1972) show a similar small increase of the directional reflectance of snow with increasing ζ. The relative increase of r from 1 to 4 for the OCEAN model is of a similar magnitude to that obtained by theoretical calculations of the radiation transfer in an atmosphere-ocean system within the wavelength interval between 0.325–0.95 μm (Raschke, 1972).

Comparisons of albedo values computed with the CLOUD-LAND model, (used in all non-snow and non-ocean cases) and the Nimbus 2 model resulted in values by the latter which were higher by a factor of about 1.1 than the former. Thus, it should be expected that the global albedo obtained from Nimbus 3 data by use of these three models would be somewhat smaller than the Nimbus 2 value. The simple assumption of a diffusely reflecting earth-atmosphere system, used by Bandeen *et al.* (1965) and Rasool and Prabhakara (1966), caused the albedo to be too low at almost all latitudes. Since reflectance models must be used to evaluate radiance measurements from satellites for

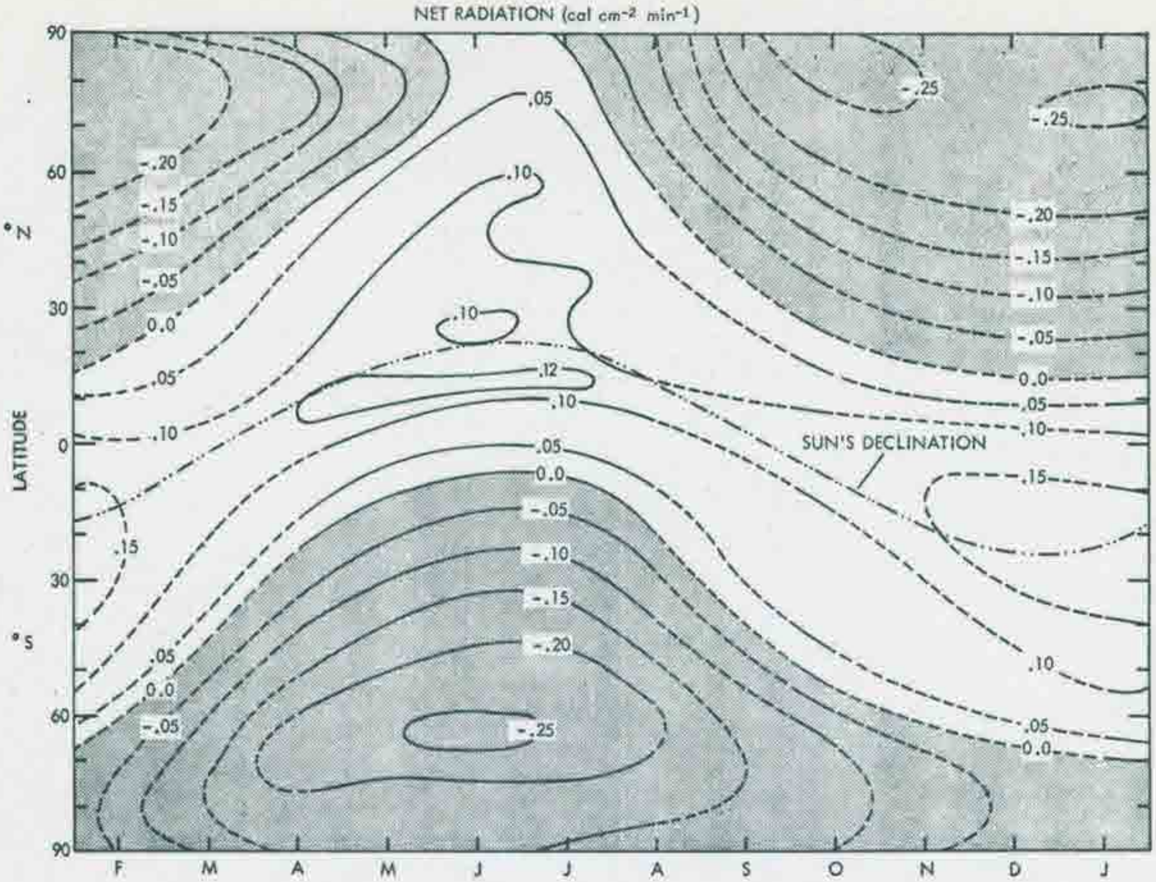

FIG. 5. Time-latitude diagram of the radiation balance of the earth-atmosphere system. Dashed portions of isopleths were found by interpolation.

radiation budget studies, the uncertainty they introduce into resulting albedo values must be considered. Based on information available today, the models used in our Nimbus 3 work are thought not to enlarge the overall experimental uncertainty of $\pm 5\%$.

c. Outgoing longwave radiation

The total radiance (4.0–200.0 μm) has been computed from concurrent radiance measurements of all four infrared channels using a multiple least-square regression formula that was derived from calculations of the radiation transfer in 160 atmospheric models representing eight climatological regimes (moist and dry atmospheres and different cloud situations). These computations were made with a program developed by Kunde (1965) and checked with one written by Wark *et al.* (1964).

Corrections for the dependence on the zenith angle

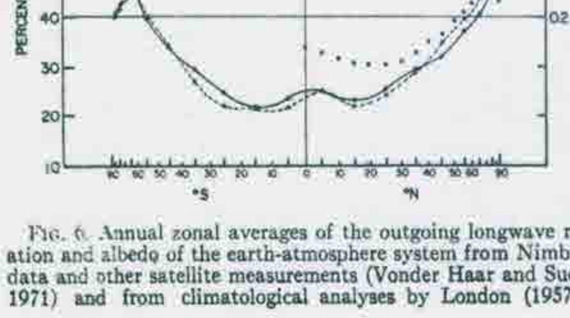

FIG. 6. Annual zonal averages of the outgoing longwave radiation and albedo of the earth-atmosphere system from Nimbus 3 data and other satellite measurements (Vonder Haar and Suomi, 1971) and from climatological analyses by London (1957).

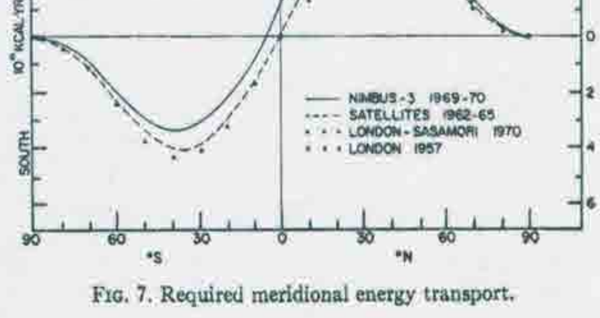

FIG. 7. Required meridional energy transport.

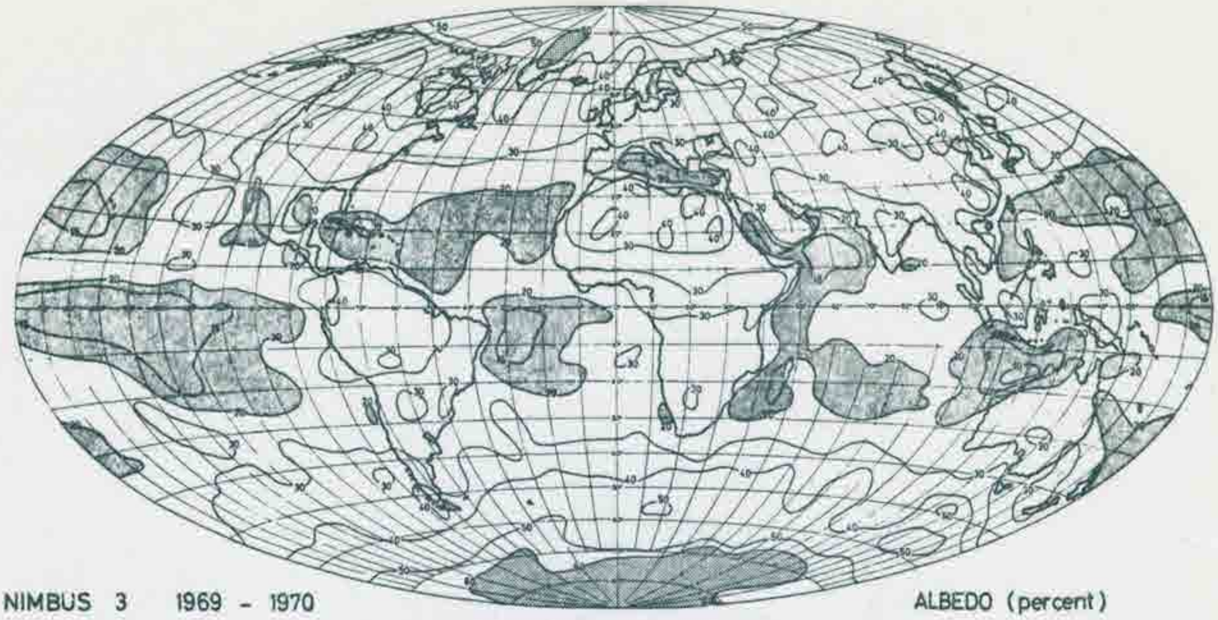

FIG. 8. Annual albedo of the earth-atmosphere system.

of measurements, θ, and the computation of the outgoing radiant emittance, W_E, were performed with a "limb-darkening" function derived statistically from samples of Nimbus 2 radiance observations in the spectral interval from 5–30 μm obtained over various areas of the earth. A more accurate approach would have been possible if a differentiation between measurements over cloud-free and cloud-covered areas could have been made.

The daily infrared averages were computed with the assumption that the values of the radiant flux density obtained from daytime (nighttime) measurements were representative for the whole daylight (nighttime) period over a grid area. These values were weighted according to the fraction of day and nighttime period of a day to account for any diurnal variation (as expressed by differences between the day and night values of the outgoing longwave radiation, measured near local noon and midnight) is remarkably large ($>+0.03$ cal cm^{-2} min^{-1}) over most continental areas at middle and lower latitudes, but very small ($\sim\pm0.015$ cal cm^{-2} min^{-1}) over most ocean areas (e.g., Raschke and Bandeen, 1970).

In the discussion of this evaluation procedure it must be kept in mind that the orbital characteristics of Nimbus 3 did not allow complete observations of diurnal variations of radiation due to both cloudiness and surface temperature changes. Such observations will be possible over limited regions with measurements from future geosynchronous meteorological satellites. However, a complete global coverage will require a system of several satellites in properly chosen orbits around the earth.

5. Results

a. *Global and hemispheric budget*

Values of global and hemispheric averages of the incoming and absorbed solar radiation, the albedo, the outgoing longwave radiation, and the radiation balance obtained from the measurements of all 10 semi-monthly periods are summarized in Table 1. The estimated annual averages for the entire earth and two hemispheres are listed at the bottom of this table. They were computed by interpolation from graphs of all semi-monthly averages, where the values of the incoming solar radiation were directly computed for missing periods. All numbers in Table 1 are written with an equivalent accuracy of 1–2%, although an overall experiment accuracy of about $\pm5\%$ (Raschke *et al.*, 1973) should be expected from the type of evaluation. They allow, even considered with less accuracy, studies of some interesting features of the seasonal variations of the earth's radiation budget, provided that those observable variations were not caused by variations in the instrumental detectivity, which could not be checked otherwise. Annual cycles have an amplitude not much larger than the assumed accuracy of 5%, but similar trends have been found from Nimbus 2 measurements (Raschke and Bandeen, 1970) and from the earlier satellite data (Vonder Haar, 1968, 1972).

In the annual average the absorbed solar radiation of 0.349 cal cm^{-2} min^{-1} (which is 71.6% of the incident radiation) is almost completely balanced ($Q_N=0.004$ cal cm^{-2} min^{-1}) by a global thermal radiation of 0.345 cal cm^{-2} min^{-1}. The difference should be considered more as an error residual than as an actual heat gain during the period of measurement. With the same

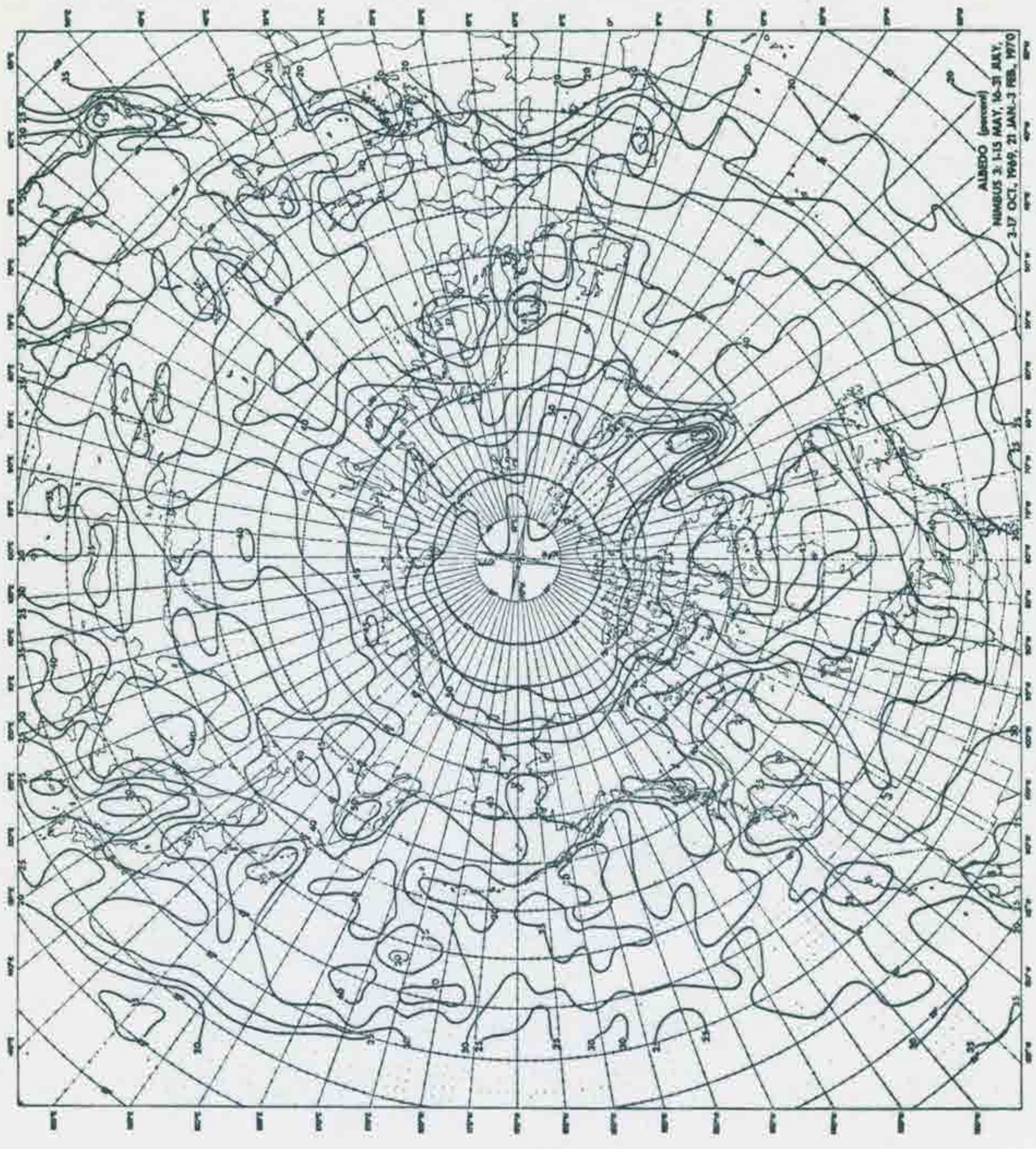

Fig. 9. Annual albedo of the earth-atmosphere system over the Northern Hemisphere.

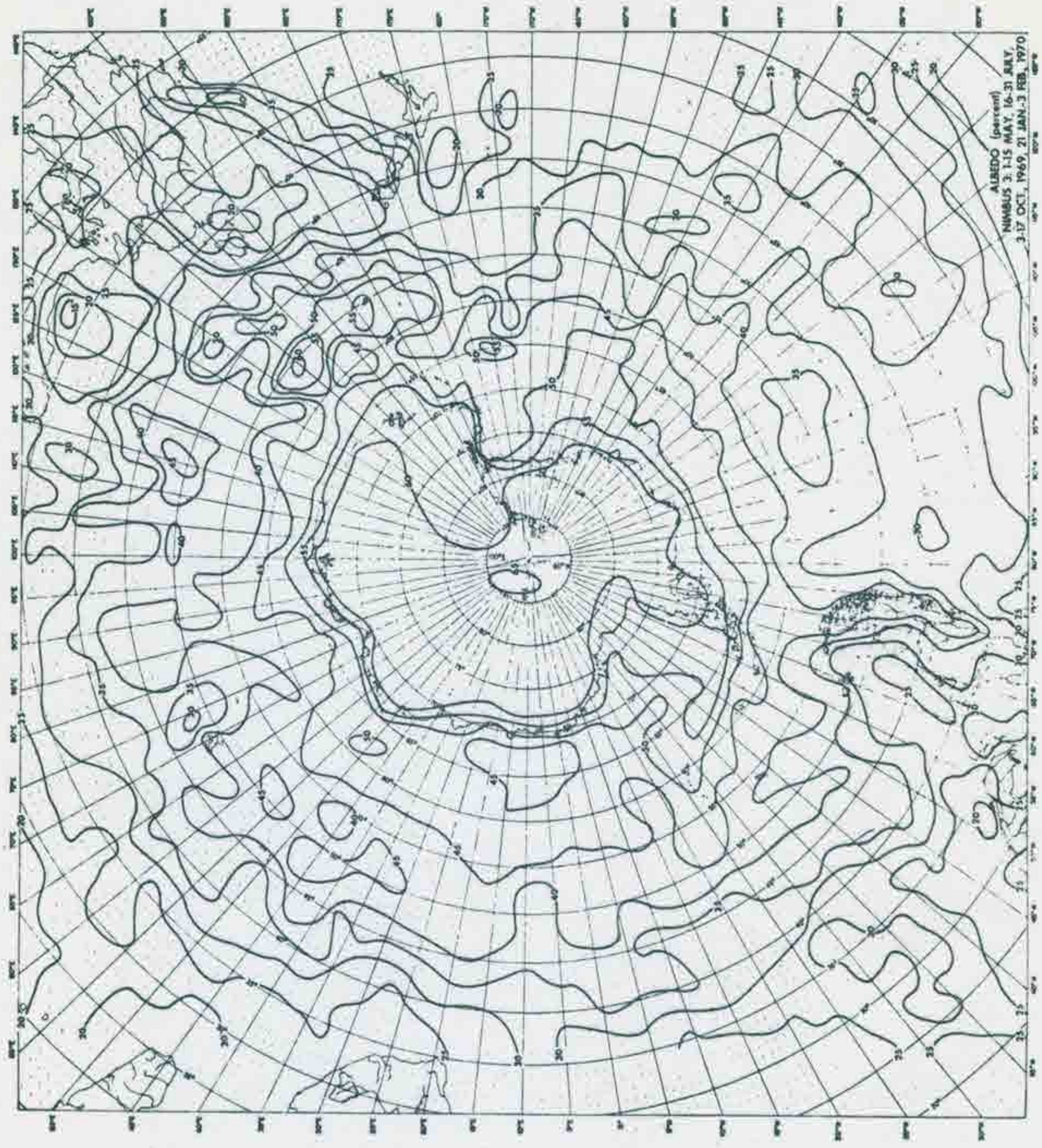

FIG. 10. Annual albedo of the earth-atmosphere system over the Southern Hemisphere.

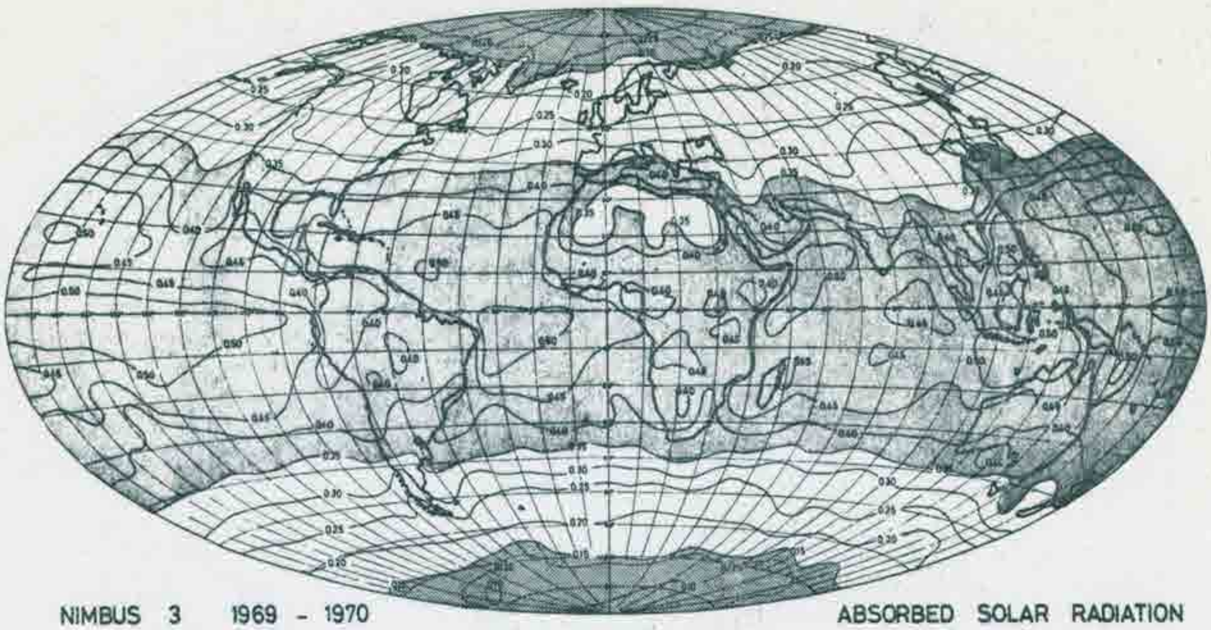

FIG. 11. Global map of the solar radiation absorbed annually in the earth-atmosphere system.

emission and insolation a global planetary albedo of 29.2% would enable complete balance. In their magnitude these values confirm results found previously by Vonder Haar and Suomi (1971) from measurements obtained from several hemispherical and flatplate radiometers on satellites during a period of more than five years. All pre-satellite investigations based on climatological data had estimated a lower global emission corresponding to $T_b \approx 250$K and a higher global albedo of more than 33%.

In their most recent calculations, London and Sasamori (1971) using the climatological data used earlier by London (1957) but with more recent absorption models, obtained a mean albedo of 29% over the Northern Hemisphere, in good agreement with the results from satellites. They obtained, however, a mean albedo of 33% over the Southern Hemisphere, a value markedly higher than either that from Nimbus 3 or that measured from other satellites. Recent calculations by Sasamori *et al.* (1971) resulted in an even higher albedo of 35% for the Southern Hemisphere.

In an objective discussion of the Nimbus 3 results in Table 1, the incompleteness of the data set and possible biasing errors in the evaluation methods preclude firm conclusions based on small differences between *large* numbers. However, averages of albedo measurements over both hemispheres show a seasonal variation which could be attributed: 1) to the well-known changes of the surface albedo due to changes in the ice and snow cover, and 2) the seasonal change of the sunlit portion of the earth. Explanation of observable variations of the global albedo are hampered by the large data gaps between those observed periods. However, our observations do not support those of Danjon who found a maximum global albedo in October. The Northern Hemisphere was warmer during its summer than the Southern Hemisphere, which shows almost no seasonal variation in infrared emission.

A seasonal variation can be observed in the radiation balance of the globe with a small deficit in the period May–August and an energy gain in October and January. One might attribute this variation to the ellipticity of the earth's orbit, which causes a seasonal change of the sun's input by about 7% (~0.030 cal cm^{-2} min^{-1}) from June to January. This variation of the balance seems to be even slightly amplified by the seasonal variation of the mean planetary effective radiation temperature.

Since these measurements from Nimbus 3 required many assumptions in their evaluation and may contain sampling errors, the results in Table 1 and their discussion here must retain a preliminary character. More definite and detailed studies of the annual and seasonal variations of the earth's radiation balance and of possible exchange mechanisms between both hemispheres as might be observed in these data require continuous and precise global satellite observations of incoming and outgoing radiation over a period covering several annual cycles.

b. Zonal radiation budget

Changing from the planetary scale to a zonal scale one can clearly observe the annual variation and

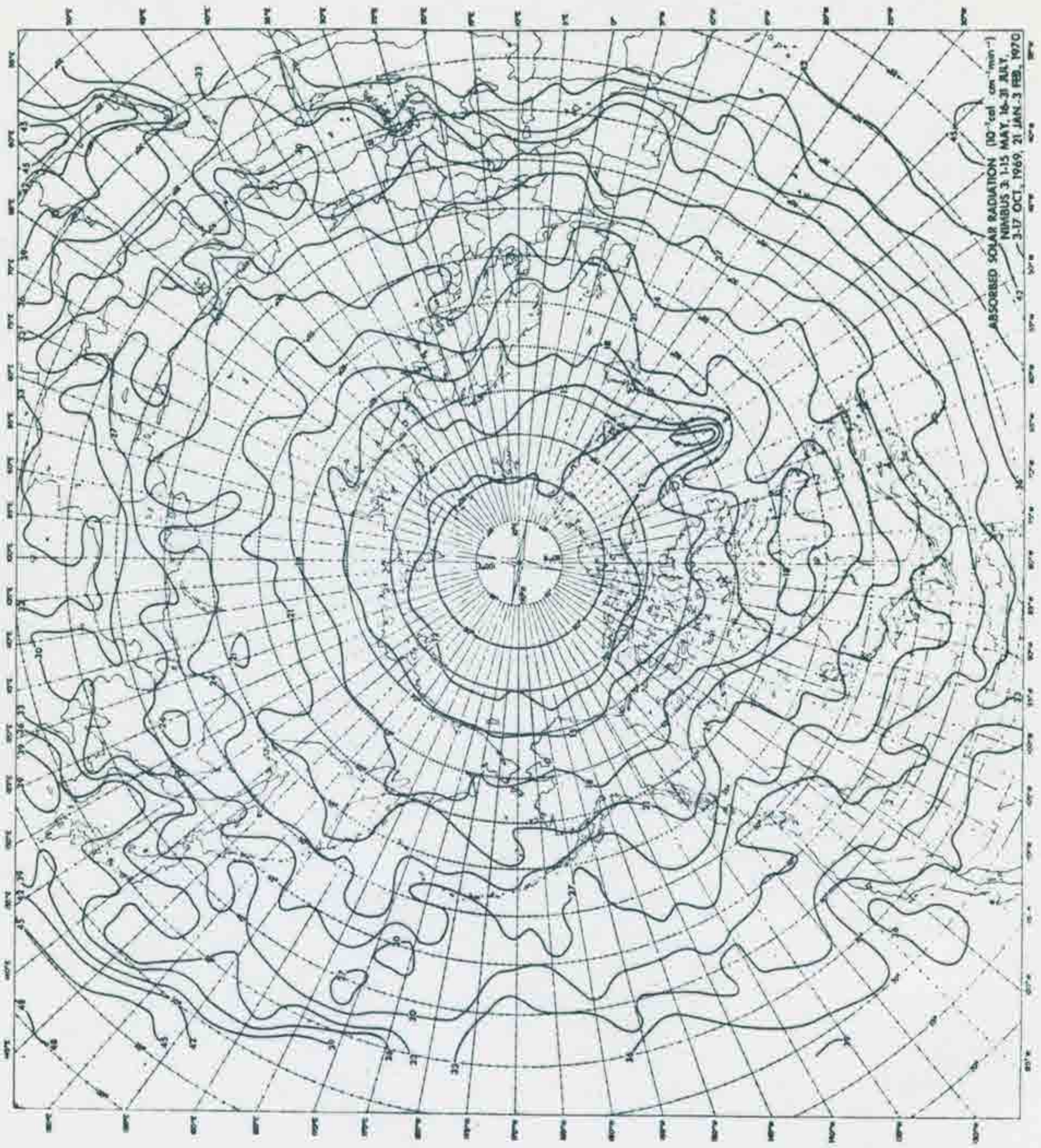

FIG. 12. Solar radiation absorbed in the earth-atmosphere system over the Northern Hemisphere.

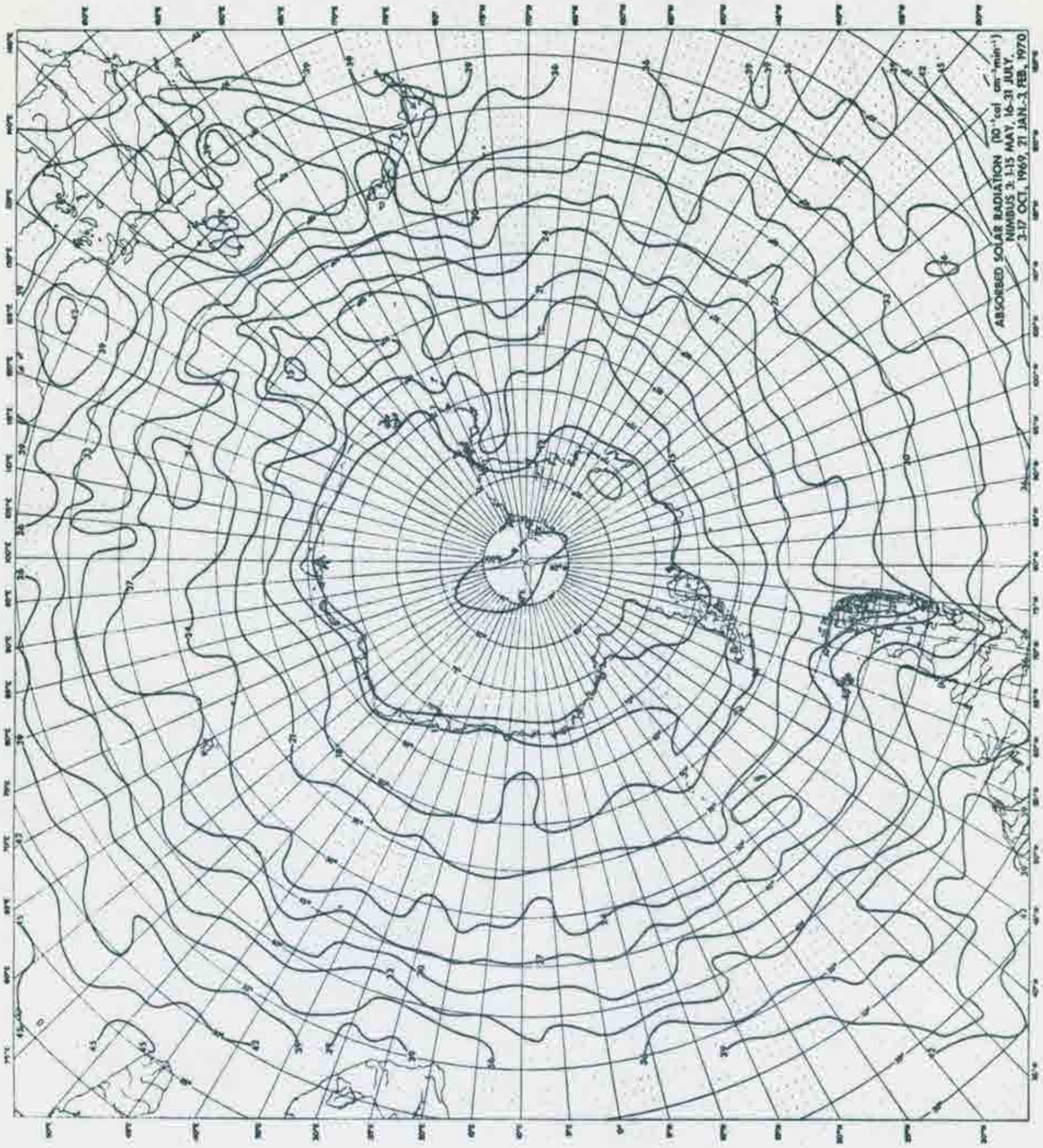

FIG. 13. Solar radiation absorbed in the earth-atmosphere system over the Southern Hemisphere.

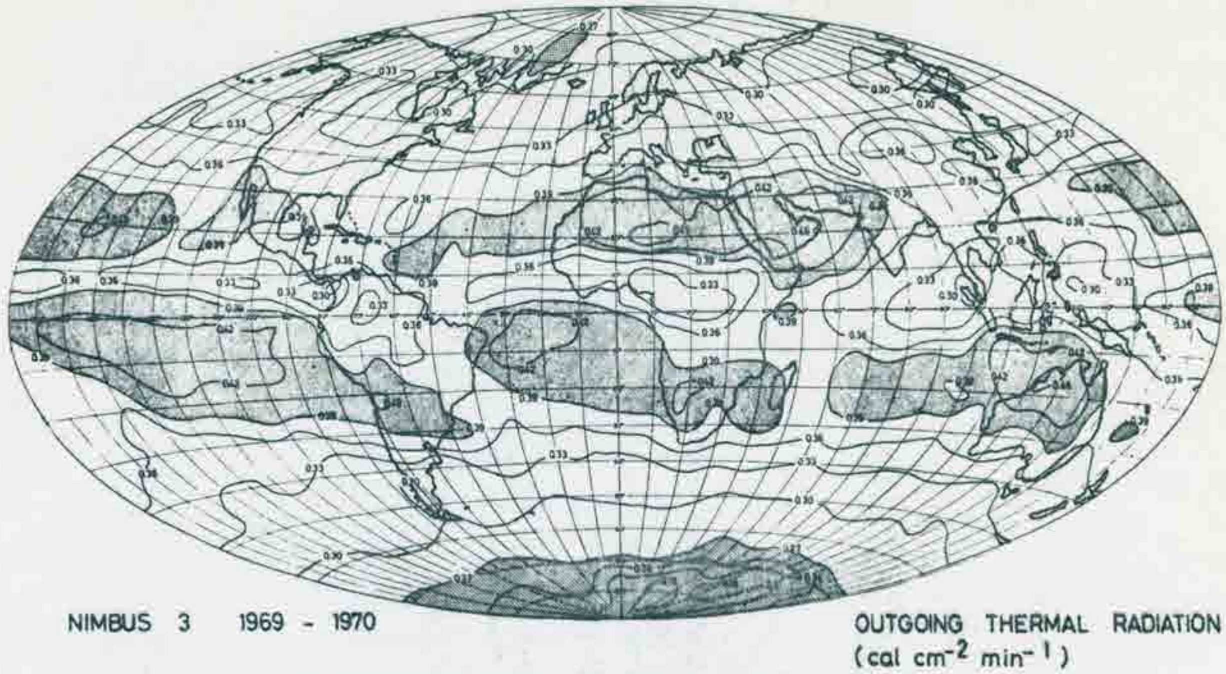

FIG. 14. Global map of longwave radiation emitted annually to space.

latitudinal distribution of the absorbed radiative energy available for circulation processes (Fig. 2), the albedo (Fig. 3), the outgoing longwave radiation (Fig. 4) and the radiation balance (Fig. 5) as demonstrated in time-latitude diagrams. Annual zonal averages of the albedo and the outgoing longwave radiation are compared with results of other investigations in Fig. 6. They were computed only from measurements during four 1970 semi-monthly periods (1–15 May, 16–30 July, 3–17 October 1969, 21 January–3 February). These measurements were assumed to be representative for these entire respective seasons.

In tropical and subtropical latitudes of both hemispheres the albedo and the outgoing longwave radiation change their magnitude due to the annual movement of the ITCZ and the Asian monsoon cloudiness. Over the northern mid-latitudes the albedo decreases rapidly from winter to summer due to melting of snow over large areas, and the continents warm up considerably. However, over the Southern Hemisphere only small variations can be observed at some latitudes, where oceans almost exclusively cover the earth's surface. The scarcity of observations during the period October–March does not allow more detailed studies of variations of the extent of antarctic icefields and of associated albedo variations.

The albedo of the northern and the southern polar regions does not exceed values of 72%, while from Nimbus 2 measurements during the period 15 May–28 July, 1966, consistently higher values had been found in the north (Raschke and Bandeen, 1970). This difference is due to the use of different evaluation models to account for the change of the directional reflectance with the sun's zenith angle (see Fig. 1). Albedo values calculated from measurements over Greenland and adjacent areas using the Nimbus 2 relation are about 1.12 times higher than those calculated with the model SNOW applied in the present study to all Nimbus 3 measurements.

For comparison of these results with surface measurements of albedo, it should be kept in mind that these results show the albedo of the earth-atmosphere system averaged over the entire spectral interval between 0.2 and 4.0 μm. Usually the albedo values obtained from ground observations are somewhat higher than those of the earth-atmosphere system, since at the ground for the most part, only radiation of the spectral range between 0.3 and about 1.5 μm will be observed, and where most surfaces will have a higher albedo than the atmosphere for the radiation of longer wavelengths which is strongly absorbed by atmospheric gases. Therefore, Nimbus 3 albedo values of only 50–70% over snow-covered regions at both poles do not contradict those of the snow and ice surface itself, which were measured to be about 75–80% (Kasten, 1963; Hoinkes, 1958; Kuhn, 1971[2]).

The variations of the albedo over the central part of the Arctic can be attributed to the melting of the snow and formations of fractures in the ice and water cover on the ice. Such structural variations do not occur over Antarctica and Greenland highlands. Thus, the changes of the albedo over the Antarctic observable from Octo-

[2] M. Kuhn, private communication.

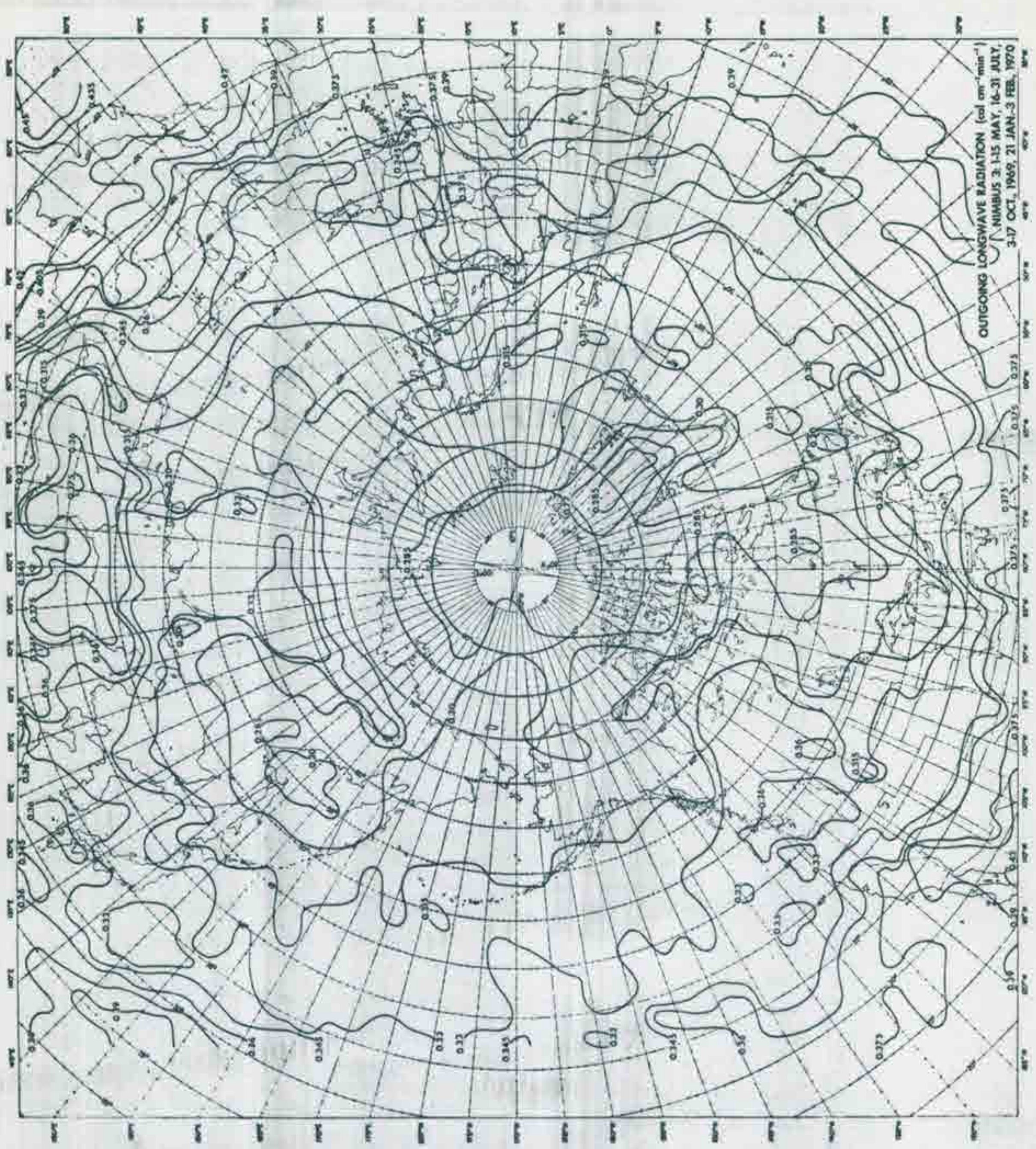

FIG. 15. Longwave radiation emitted annually to space from the Northern Hemisphere.

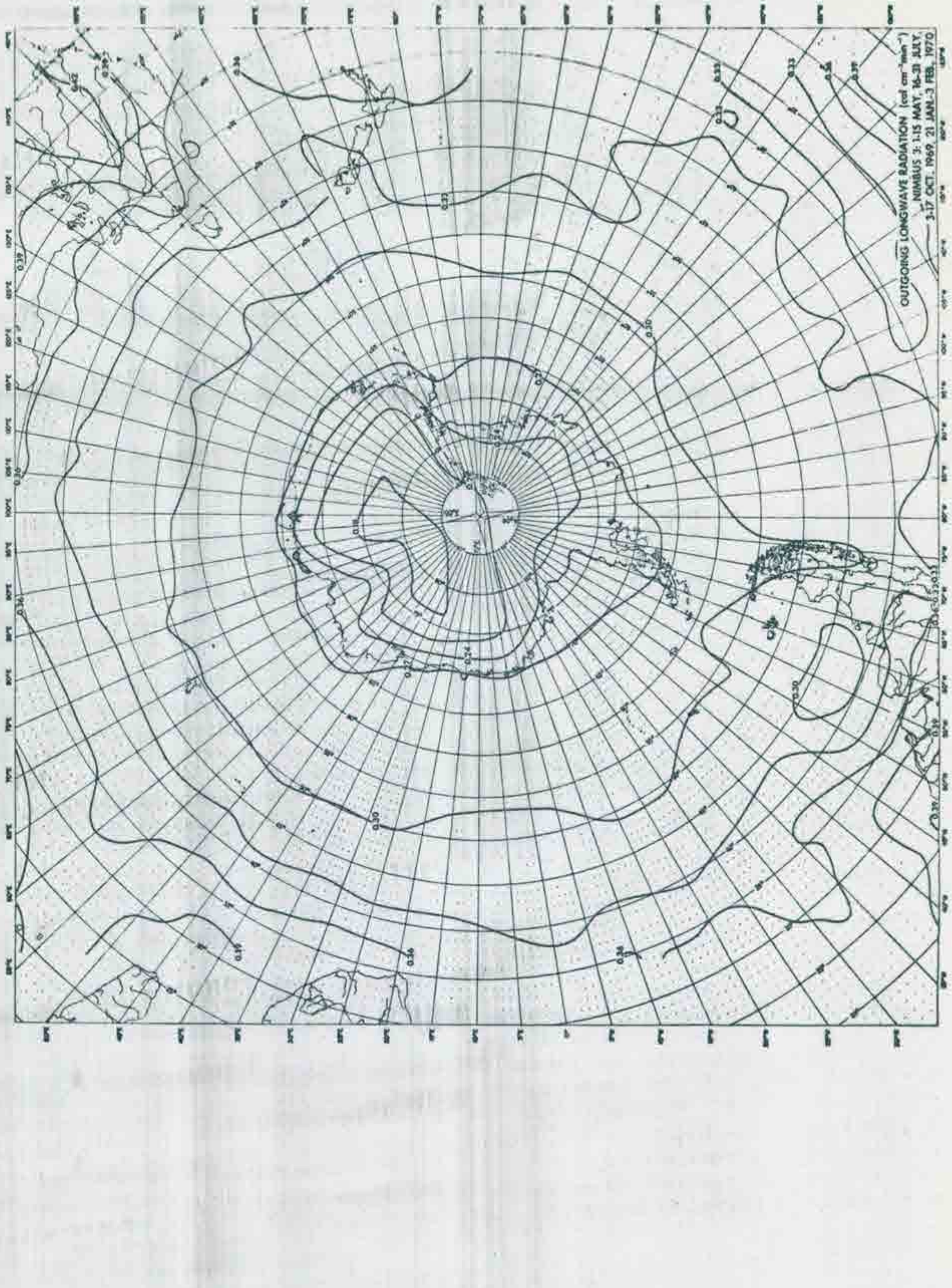

FIG. 16. Longwave radiation emitted annually to space from the Southern Hemisphere.

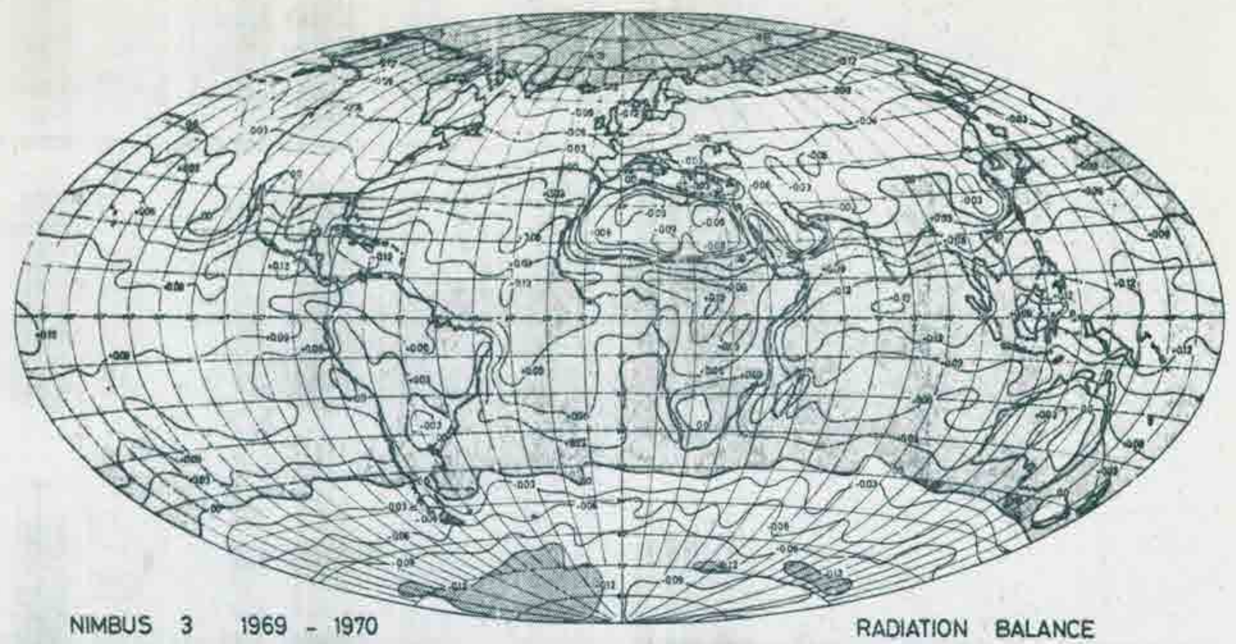

FIG. 17. Annual radiation balance of the earth-atmosphere system.

ber to January might be caused to some extent by improper corrections of the dependence of the Antarctic albedo on the angle of insolation.

The seasonal change of the radiation balance (Fig. 5) is dominated by seasonal variations of the insolation and demonstrated with the curve showing the sun's declination. Areas of major gain of radiative energy in each corresponding season are the subtropical belts, while a major deficit is found poleward of about 60° latitude. Over the Southern Hemisphere a reversal of the gradient of the radiation balance is caused by very low emission from the cold and high plateaus of the Antarctic continent during winter 1970.

The comparison of *annual* zonal averages of the albedo and the outgoing longwave radiation obtained from Nimbus 3 data with those from other satellite observations (Vonder Haar and Suomi, 1971) and from calculations with climatological data (Fig. 5.5) shows clearly that in the early calculations (London, 1957) the cloudiness and/or its effects on the transfer of shortwave and longwave radiation has been overestimated, particularly in lower latitudes. There the earth-atmosphere system absorbs approximately 40% more radiation than previously assumed. The Nimbus 3 data resulted in a much higher radiation deficit over the arctic than over the antarctic primarily due to higher mean annual effective radiative temperature over the former area.

The required latitudinal transport of energy (Fig. 7) has been calculated from the measurements by distributing the global net gain of 0.004 cal cm^{-2} min^{-1} (Table 1) equally by area over the entire globe to obtain balance. This implies the assumption that no energy had been stored in the system during the measurement period 1969–70. Results show a northward cross-equatorial transport of about 1.1 10^{22} cal year^{-1} and a much higher required transport at 30–40° latitude than at the same southern latitudinal belt. Results derived from earlier satellite measurements and from computations show energy transport requirements which are nearly symmetrical to the equator with almost no transport through the equator. These latter results were obtained from averages of measurements and other observations over many years and may much better represent, therefore, the mean behavior of the energy transport in the earth-atmosphere system, whereas the Nimbus 3 data pertain only to four 15-day periods of one specific year. In addition, the cross-equatorial transports inferred from all satellite data are very close to the error level resulting from 5% measurement accuracy. Therefore, it cannot be concluded, yet, from these measurements whether a northward atmospheric transport of 0.4 10^{22} cal year^{-1}, as found recently by Oort (1971), is required to be accompanied by a simultaneous transport in the oceans in the same direction. On the other hand, several authors (e.g., Flohn, 1967) explained the asymmetrical circulation patterns over both hemispheres on the basis of different radiation budgets. Although Vonder Haar and Suomi (1971) did not observe different hemispheric radiation budgets in the mean, satellite observations over several years will enable observations of *interannual* variations of the

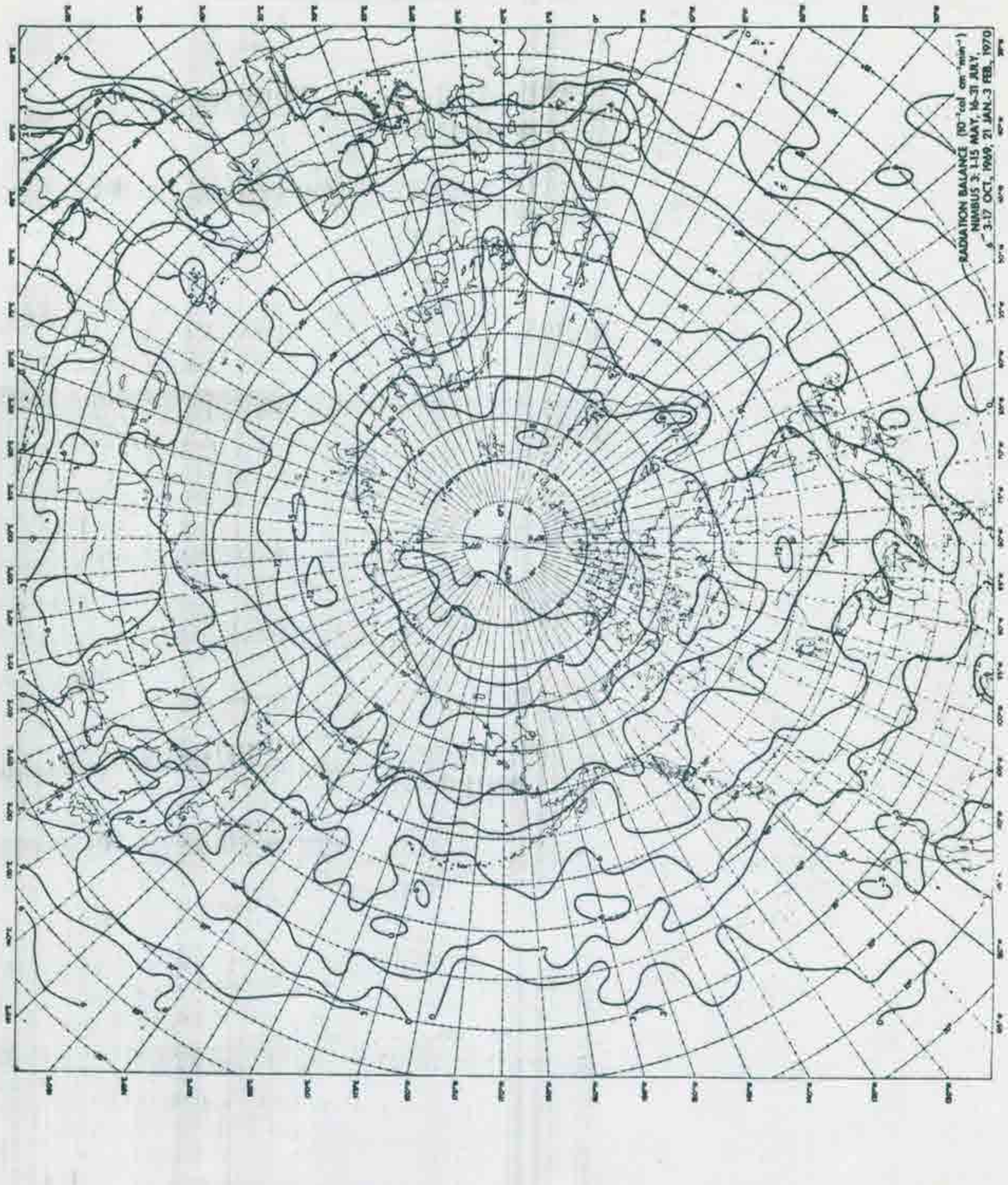

FIG. 18. Annual radiation balance of the earth-atmosphere system over the Northern Hemisphere.

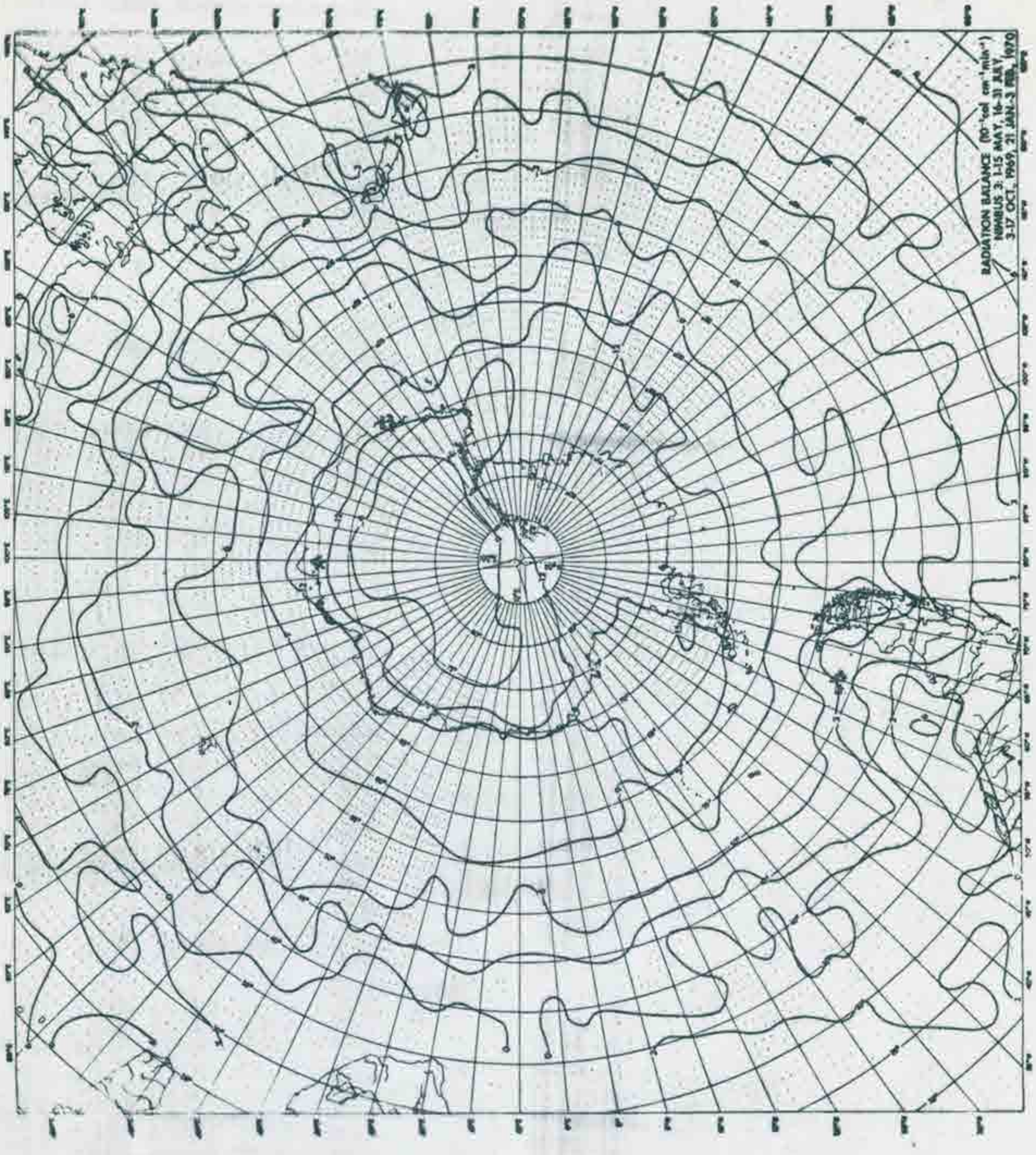

FIG. 19. Annual radiation balance of the earth-atmosphere system over the Southern Hemisphere.

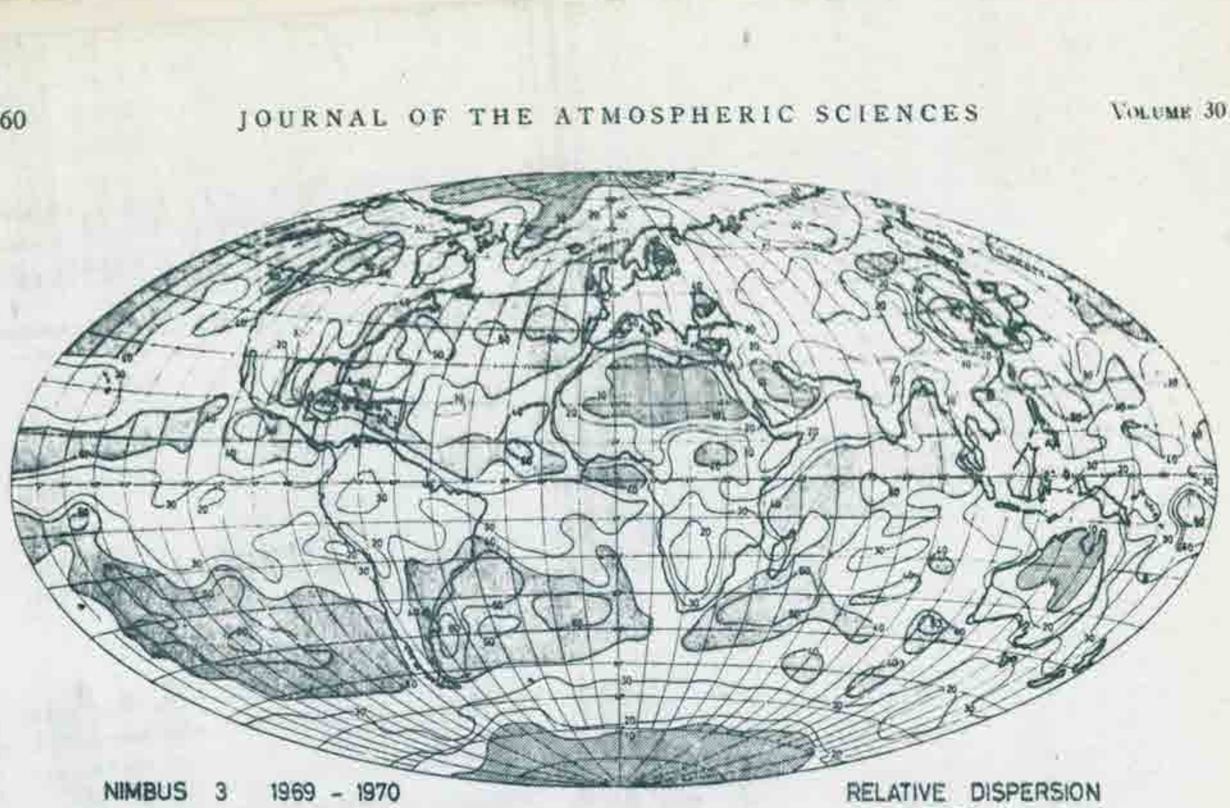

FIG. 20. Relative dispersion of the annual albedo of the earth-atmosphere system.

transport requirements implied by the comparisons of Fig. 7.

c. Geographical distributions

For the calculation of global distributions of all annual averages of radiation budget parameters, again only results of absorbed solar radiation and the outgoing longwave radiation derived from measurements of only four 1970 semi-monthly periods (1–15 May, 16–30 July, 3–17 October 1969, 21 January–3 February) were used. These measurements were assumed to be representative for their entire respective seasons. The sun's irradiance at the top of the atmosphere was obtained independently from geometrical considerations.

Results are shown here in global Aitoff projections with a spatial resolution of about 500 km×500 km for each grid point in low-latitude regions and for a better resolution of the patterns over polar regions (250 km ×250 km) in true polar-stereographic projections covering each pole (Figs. 8–19).

The patterns in the albedo map (Fig. 8) clearly reveal the land-sea distribution and the general circulation as it is represented by the mean cloud patterns over both hemispheres. The small continents alone would cause a more zonal pattern over the Southern than over the Northern Hemisphere. The high reaching convective clouds associated with the ITCZ and partly with the Asian monsoon appear as a belt of relatively high albedos of more than 25–30%, and low emission of less than 0.33 cal cm^{-2} min^{-1} (Fig. 14). Low persistent stratus clouds along the western coastal areas of North and South America and Africa do not appear in the map of outgoing longwave radiation, but appear with albedo between 25 and 35% (see Vonder Haar, 1970). The albedo of both polar regions (Figs. 9 and 10) is considerably higher than 50%. The patterns are closely associated with permanent and dense ice fields. Regions of major absorption of solar radiative energy (Figs. 11 and 12) are the oceanic areas in the subtropics of both hemispheres. They are also the areas of the major gain of radiative energy (Figs. 17 and 19) of more than 0.06 cal cm^{-2} min^{-1}, while the African and Arabian deserts at the same latitude have a radiative deficit of more than 0.03 cal cm^{-2} min^{-1}. Especially in contrast to regions to the east and west, such deficit areas in the tropics stimulate thoughts of large-scale east-west circulations. The Saharan deficit might be energetically balanced by subsidence warming associated with a direct circulation having an ascending branch over the summer monsoon area. Both polar regions, poleward of about 45° latitude, are in the annual average deficit areas with a surprisingly smaller deficit (due to low emission; see Figs. 14 and 16) over the South Pole.

Additional Nimbus 3 radiation budget results (for the four seasonal periods) are presented in map form by Raschke *et al.* (1973).

d. Temporal variability of the radiation balance

The temporal variability of the albedo over each grid field can be demonstrated in a map of the relative dispersion, as shown in Fig. 20, which is the ratio of standard deviation to the mean value. This map was computed from the daily averages of the albedo in each grid field obtained from measurements during the same four semi-monthly periods. The values include all temporal scales of variations between the annual cycle and day-to-day changes of temperature, cloud cover and height, and surface albedo. The partition of each of these components can be considered on an annual basis only with a more complete data set (Vonder Haar, 1972), while the variability on a monthly basis has been considered elsewhere (Raschke and Bandeen, 1970).

Patterns in this map reveal some of the changes due to traveling disturbances. Over the oceans very large relative dispersion of the albedo is due to the contrast in the albedo between clouds and the open sea.

In the map high values of the relative dispersion can be attributed to the varying cloud cover at the equator and to areas of preferred dynamical and convective activity over both hemispheres. Relatively low dispersions are found over the subtropics and over both polar regions. Also, those areas known to be covered with persistent but low stratus decks appear in these maps with small values of the relative dispersion. Such features have been discussed already in a preliminary study (Raschke and Vonder Haar, 1971).

e. *Deviations from zonal means*

Longitudinal variations of the radiation fields are heavily overshadowed by the equator-to-pole gradients in all maps of the annual radiation budget, especially of those quantities containing as one component the incoming solar radiation. The removal of this gradient, simply done by subtraction of the zonal average from each grid value, then clearly reveals the departures from a zonal structure, which are due to surface properties and cloud fields and may cause an additional (and comparatively weaker) longitudinal forcing of our atmosphere's circulation.

In the map of the outgoing longwave radiation (Fig. 21), the negative areas are those with comparatively large and high cloudiness. These are the major cyclonic tracks over the Southern Hemisphere, the monsoon cloudiness over the Indian Ocean and over Southeast Asia, and convective cloudiness over most tropical continental areas and the Malayan Archipelago. Apparently, Northern Hemisphere storms have a less persistent zonal component. The high-reaching ice fields of Greenland and the Antarctic continent are also considerably cooler than their surrounding areas.

Almost all continental areas and also the aforementioned fields of permanent cloudiness were found to have lesser surplus or higher deficit of radiative energy than adjacent ocean areas (Fig. 22) which is primarily due to their higher surface albedo. The highest relative deficits of more than 0.09 cal cm^{-2} min^{-1} were found over South America and the North African and Arabian deserts.

f. *Minimum albedo*

Estimates of the albedo of the ground and also locations of persistent cloud fields and of ice and snow cover can be made when traveling or otherwise changing cloud fields are removed by displaying only the lowest albedo value in each grid field. This approach is based on the simple assumption that the albedo of the earth-

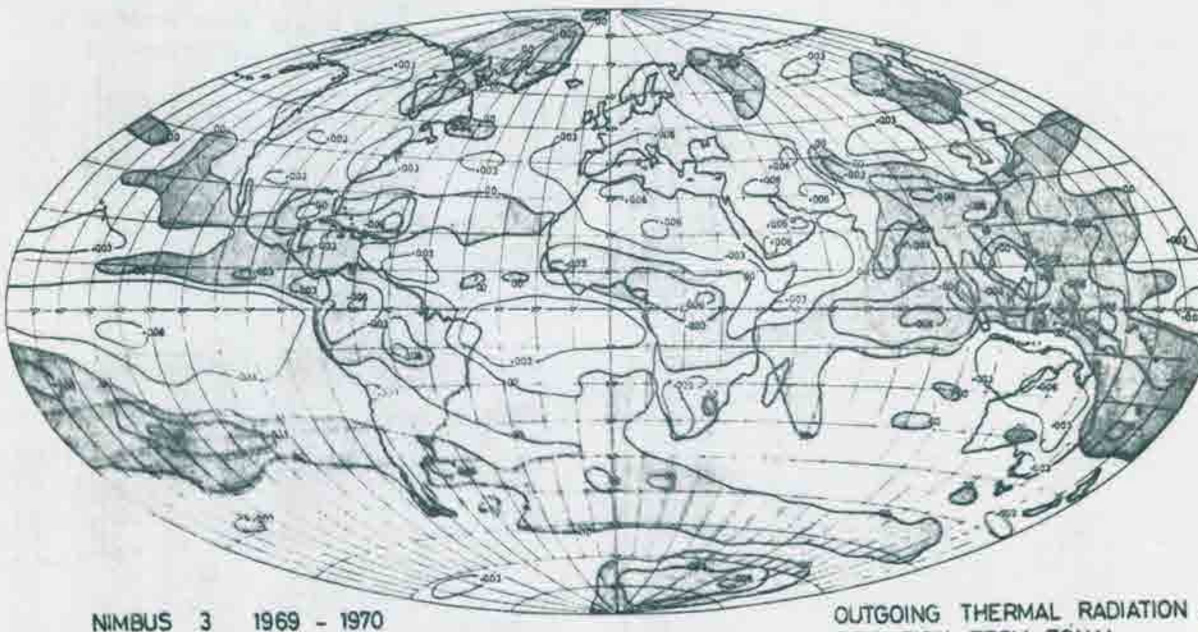

FIG. 21. Deviation of the outgoing longwave radiation from zonal average.

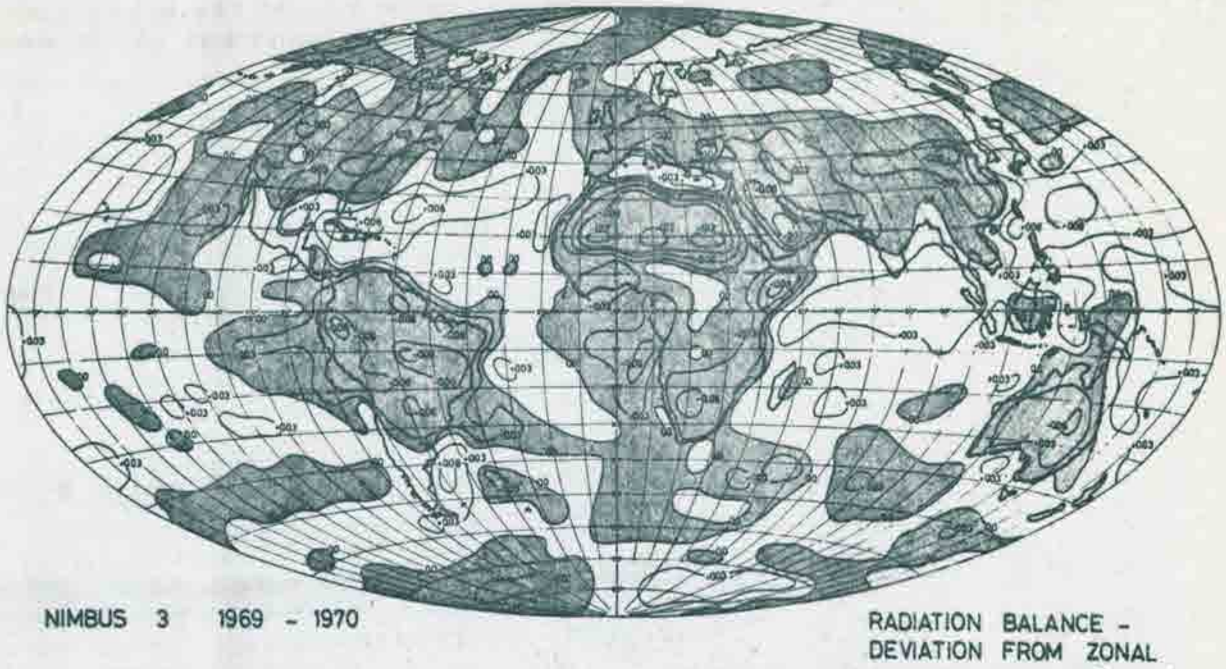

FIG. 22. Deviation of the radiation balance from zonal average.

atmosphere system is higher over each area in the presence of clouds than for a cloud-free atmosphere. Further, the instrumental noise should have been removed considerably by averaging of a sufficiently large number of single observations within each grid field. Made on an annual basis, as shown in Fig. 23, these maps will allow estimates of the effective surface albedo of continental areas, after the atmospheric interference has been removed properly. Note also the aforementioned areas of persistent cloud cover and that other regions over equatorial areas with apparently no cloud-free days can be located. Most ocean areas between 50N and 50S were found with minimum albedos $<10\%$, but not smaller than 4%. At higher latitudes

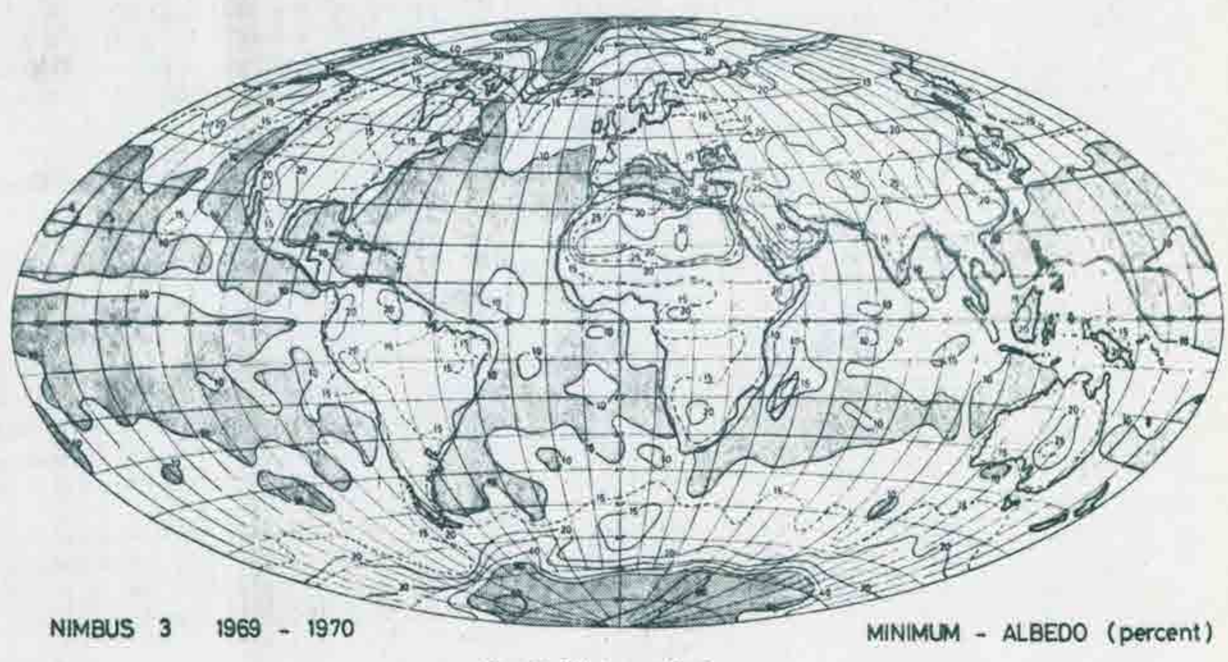

FIG. 23. Minimum albedo.

the cyclonic activity prevents observations of completely cloud-free areas in this scale. Minimum albedos >40% belong to ice fields at their observed smallest extent during July over the arctic and during January over the antarctic, respectively.

6. Summary and conclusions

This paper has discussed results of measurements of the 1969–70 annual radiation budget of the earth-atmosphere system and its components. The data were obtained from a temporally incomplete but relatively accurate set of radiation measurements from the meteorological satellite Nimbus 3 during 1969–70. They are presented on global, hemispherical, zonal and high resolution scales.

Despite the errors introduced primarily by the evaluation method and assumptions, and by the incompleteness of the data set, these results provide a basis for checks of the local and global annual energy budget of numerical circulation models. The magnitudes of the global annual albedo of 28.4% and of the outgoing longwave radiation, which corresponds to an effective radiation temperature of about 255K, confirms previous results from satellite data of a darker and radiatively warmer planet Earth than was believed earlier on the basis of calculations using climatological data. These values nearly balance on a global scale the incident solar radiation computed for a solar constant of 1.95 cal cm^{-2} min^{-1}. The required poleward energy transport obtained was found smaller over the Southern than over the Northern Hemisphere during 1969–70 in contradiction to the earlier investigations summarized by London and Sasamori (1971). These results, however, cannot be considered to be representative for a typical annual cycle, basically due to lack of measurements during several months of this particular period. It is therefore concluded that further satellite experiments of similar or even better accuracy than the Nimbus 3 experiment are required to obtain measurements with a high *relative* accuracy over a period of more than 10–15 years, thus permitting radiation balance studies lasting over this entire period. These measurements should include observations of the important components of incident solar radiation since the sun's output of radiative energy may undergo variations of several percent as discussed by Kondratiev and Nikolsky (1970), although there is some doubt that the sun is at present such a variable star.

Once such observations are available, base lines can be established to permit subsequent observations of climatic trends that may result from natural causes on earth, human activities, and/or changes in the spectral energy radiated by the sun.

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Measurements of the energy exchange between earth and space from satellites during the 1960's

Abstract

The net radiation budget of the earth-atmosphere system can be obtained from satellite measurements of the infrared radiant exitance and reflected and scattered solar radiation along with a knowledge of the solar constant. During the 1960's experimental and operational meteorological satellites carrying thermistor bolometer sensors designed for this task were in orbit during about 60 months. Our paper presents a synopsis of results from these measurements, including: a global planetary albedo of 30%, long-term global radiation balance within measurement accuracy (2–3%), the net equator-to-pole radiation gradients (and their variation) that drive our atmospheric and oceanic circulations, as well as selected measurements of radiation budget terms over particular geographical areas. Future satellite experiments are planned to allow measurements of higher precision and with better space and time sampling. However, the results thus far have provided a solid descriptive base for more detailed diagnostic studies, especially regarding the significance of observed interannual radiation budget variations and also the separate consideration of energetics of the atmosphere and the ocean.

1. Introduction

While atmospheric scientists have been interested in the global radiation budget for more than 100 years, measurements have been available only in the last twelve years. Earth-orbiting satellites provided the platform for radiation budget measurements; first experiments were flown on Explorer VII in 1959.

As in earlier days, our desire to study the radiation budget is high because:

a) global climate is a result of the total energy exchange (by radiation) between our planet and space

b) the large-scale atmospheric and oceanic circulations are forced fundamentally by the gradient of radiation exchange with space between pole and equator

and c) local area radiation budgets at the "top of the atmosphere" are in an important boundary condition for local and regional energetics that affect both the physical and biological processes in the region of interest.

In recent years, radiation budget measurements from satellites have also been recognized as important controls for checking the performance of numerical models of the atmosphere's circulation on a global scale.

Fig. 1 shows a schematic diagram of the terms of the radiation budget of the earth-atmosphere system. Three terms are shown, with the net radiation or radiation budget, Q_n, as the residual of:

$H_S(\lambda, \Phi, t)$ – the direct irradiance of solar energy at $p = 0$ (computed from an assumed value of the solar constant, $S_0 = 1.95 \text{ cal} \cdot \text{cm}^{-2} \cdot \text{min}^{-1}$)

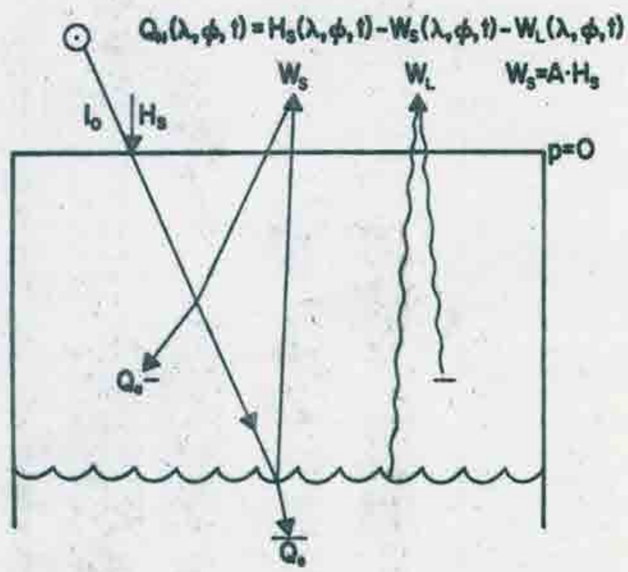


Fig. 1
Schematic depiction of the radiation budget of an earth-atmosphere column.

minus $W_S(\lambda, \Phi, t)$ – solar energy reflected and scattered from clouds, atmospheric gas and aerosol, and the surface (measured from the satellite)

minus $W_L(\lambda, \Phi, t)$ – the infrared radiant exitance from clouds, atmospheric constituents and the surface (measured from the satellite)

All dimensions (as the solar constant) are energy per unit area and unit time. The functionals (λ, Φ, t) refer to longitude, latitude and time. They serve to note the time and space scale dependence of the radiation budget; or schematic box could apply to a unit area at some location or to the entire global envelope. Note that the planetary albedo, A, is the ratio W_S/H_S.

Two basically different types of radiation budget experiments have been flown on U.S. satellites (5), (4).

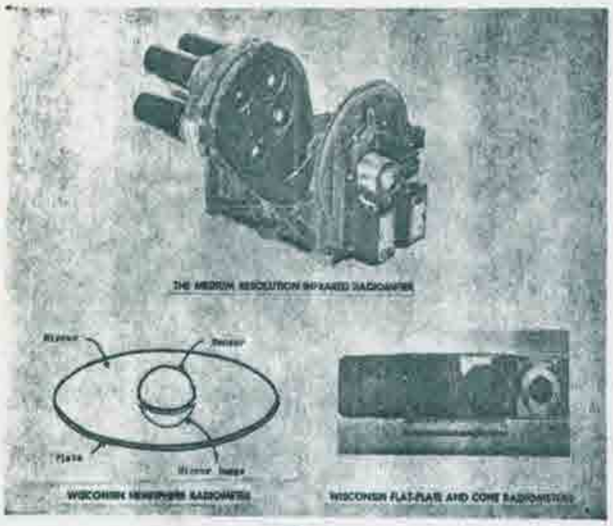


Fig. 2
View of the radiation budget sensors flown on U.S. satellites during the 1960's.

They are shown in fig. 2 as:

a) the medium resolution infrared radiometer; it has a narrow angle (5 degree) field of view, scanning capability by rotating a mirror, four infrared channels and one to measure the radiance of reflected solar radiation.

and b) omnidirectional ($2\ \pi$ sterdian) sensors named the Wisconsin hemisphere or Wisconsin plate radiometers (cones provide special checks for these omnidirectional sensors); they always consist of matched pairs of black and white sensors, the former to measure all radiation (solar and infrared), the latter only the infrared.

Both types of experiments use the same radiation detectors, thermistor bolometers. All other experiment parameters (field-of-view, time constant, spectral response, and method of data reduction) differ. Furthermore, the basic radiation measurement (of the radiation budget parameters shown in fig. 1) for the scanning radiometer is *radiance*, while the omnidirectional sensors measure *radiant power*. Data reduction techniques (more complex for the scanning radiometer data) are employed to derive the desired values of $W_S\ (\lambda, \Phi, t)$ and $W_L\ (\lambda, \Phi, t)$. From the viewpoint of scientific use, either system should be acceptable for studying the earths radiation budget. However, the more complex scanning radiometer system does provide radiation budget measurements at one order of magnitude finer on the space scale. Both experiments undergo absolute calibration before launch into space. In addition, the omnidirectional sensors are checked against the direct solar energy during each orbit; the scanning radiometer views a reference source of known temperature on the satellite. In this way, relative calibration in space is provided for all measurements by the Wisconsin experiment and for the infrared measurements from the scanning radiometer. Reflected solar radiance measurements from the latter are checked against regions on the earth such as deserts.

2. Results for the entire earth and for latitude zones

VONDER HAAR and SUOMI (8) have discussed results from satellite experiments in orbit before 1967. RASCHKE and BANDEEN (6) have discussed two-and-one-half months of 1966 scanning radiometer data in detail. Both of these references cite numerous previous papers dealing with both the methods of data reduction and special studies using the radiation budget measurements. The present paper discusses all of the measurements available thus far, including those acquired from NIMBUS-III in 1969 and 1970.

Table 1

Global Radiation Budget			
	Satellites 1962—1966	Nimbus-III 1969—70	Meteor-II 1969—70
MAM	.33 (30%)	.35 (29%)	.37
JJA	.34 (26%)	.35 (28%)	.37
SON	.34 (28%)	.35 (28%)	.37
DJF	.33 (31%)	.34 (29%)	.35
Annual	.34 (30%)	.34 (29%)	.36
*Annual net Radiation	.00	.00	—

Table 1 summarizes the measurements of the annual and seasonal radiation budget of the entire planet. First value is infrared radiant exitance, W_L; followed by planetary albedo (A). Accuracy estimates for the results of the U.S. experiments are plus-or-minus one unit of the least significant digits shown; this yields relative measurement accuracies of about 3 %.

For the annual case, both the earliest satellite data set (1962—66) and the most recent (1969—70) show that our earth-atmosphere system has a planetary albedo of 29—30 %, outgoing infrared radiation to space averaging $0.34\ \mathrm{cal} \cdot \mathrm{cm}^{-2} \cdot \mathrm{min}^{-1}$, and net global radiation balance (within measurement accuracy) when the solar constant is $1.95\ \mathrm{cal} \cdot \mathrm{cm}^{-2} \cdot \mathrm{min}^{-1}$. The infrared emission is equivalent to a black-body emperature of (255° K), higher than the value estimated by LONDON (2) before the satellite experiments. Also, our planet is darker than was previously believed; it has a lower albedo than the early value of 35 %. Recall that these results have now been obtained from two different types of satellite experiments, thus giving further assurance of the accuracy of both data sets.

Seasonal variation of the planetary radiation budget is small. A very small tendency for a brighter and colder planet during the period December — May is seen in both sets of U.S. data. Infrared experiments on METEOR satellites in 1969—70 (1) also detected a slightly colder earth during the Northern Hemisphere winter.

The annual case is especially interesting when we relax the space scale and consider the satellite measurements gathered into averages for each specific latitude zone. Fig. 3 shows the resulting mean meridional profiles for (a) the satellite measurements, 1962-66, (b) NIMBUS-III results and (c) the estimates by LONDON (2) in pre-satellite days[1]). As in the global case (table 1) the satellite sets show general agreement even though they were not obtained during the same years. All measurements differ strikingly from the estimates of planetary albedo in the tropics. The darker planet noted previously is due primarily to a lower albedo in the region $0-30°$ N than was previously believed. Apparently, the calculation of LONDON and others more than ten years ago used over-estimates of opaque (reflecting) cloud amount in the tropics. Separate evidence for this has been noted by VONDER HAAR and HANSON (1969). They found that the measured solar radiation reaching the surface in the tropics is greater than all previous estimates.

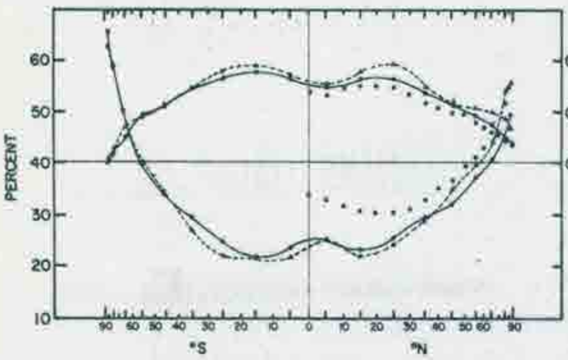


Fig. 3
The annual values of infrared radiant exitance W_L (top); and planetary albedo, *A*, (bottom) along a mean meridional cross-section as measured from satellites during 1962—66 (solid) and from Nimbus III, 1969—70 (dash); and as calculated by (2) (dot).

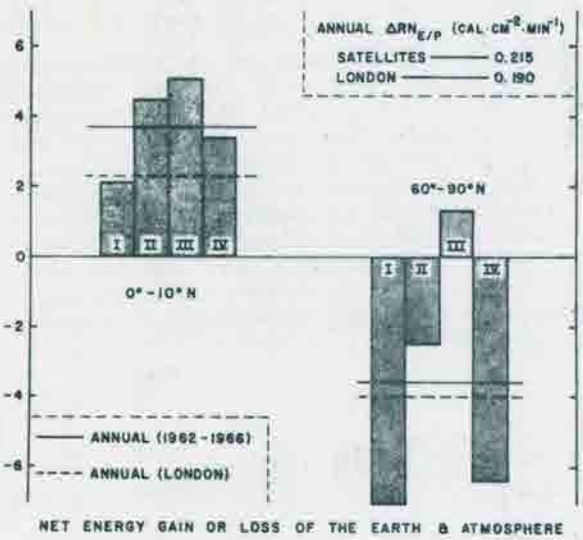


Fig. 4
Energy gain and loss in latitude zones as measured from satellites (after (8)).

Infrared radiation to space is measured to be slightly greater than was calculated at all latitudes. The significance of the overall differences between measurements and earlier calculations is seen in fig. 4. Here, the net energy gain or loss of two earth-atmosphere zones is shown for the annual time period (horizontal lines) and for mean seasonal conditions (shaded bar, $I = DJF$). LONDON's results for the annual case are also shown. In the region $0-10°$ N much more energy (1.5×10^{16} cal · min^{-1}) is gained during the year than was previously estimated. At polar regions the old and new values are much closer, giving the same depiction as would have been inferred from fig. 3: more energy gained by our atmosphere and oceans at low latitudes, the need for increased poleward energy transport, slightly increased energy loss to space throughout the mid-latitudes.

Most of the energy gain is to the tropical oceans. Thus, the required increase in poleward transport must be accomplished by either direct sensible heat flux by the oceans, or increased air-sea energy exchange followed by energy transport in the atmosphere through some combination of the sensible, potential and latent energy mechanisms. On a seasonal basis, the energy gain and loss shown in fig. 4 varies in the expected relative pattern. Note, however, that a small net energy gain is measured over the North polar cap during summer. This energy, together with that advected from lower latitudes combines to allow the warming of air and melting of surface snow and ice characteristic of that season.

3. Measured variation of the radiation gradient from equator to the poles

In the previous section we have seen the results and hypotheses that are based on consideration of the satellite radiation budget measurements over a long time scale (5−6 years). Of special interest also are the measured values in specific seasons and their inter-annual variation. Fig. 5 displays a simple index, $\Delta RN_{E/P}$, used as a first look at the fundamental net radiation gradient between equator and pole. On the

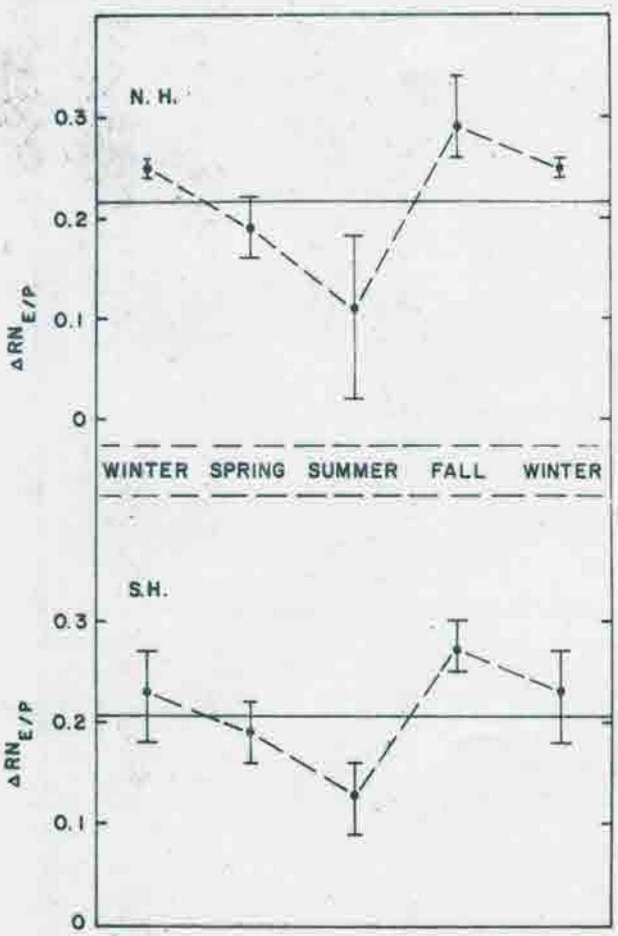


Fig. 5
Values of the index of radiation gradient from equator to pole in both the Northern and Southern hemispheres (see text). (After (8)).

[1]) BOLLE (1971) compares the satellite measurements of VONDER HAAR and SUOMI (8) ((a) above) with very recent, new estimates by LONDON and SASAMORI (3). The new estimates are now in much better agreement with the measurements.

very longterm this gradient depicts the thermal forcing of our earth-atmosphere system; values of the mean annual gradient for both the northern and southern hemispheres are shown as horizontal lines in fig. 5. They are nearly the same, with the northern hemisphere slightly larger.

The same figure shows mean seasonal values (dots) and the range of gradients measured from satellites in specific seasons (range bars). In both hemispheres the gradient is least in summer and greatest in fall, with the most abrupt change between these two seasons. Mean winter values are less than those of fall due to a gradient reversal in polar regions not considered by our simple index. Therefore, the fall and winter values should be considered practically the same in the mean.

Measured variation had been the least in Northern Hemisphere winter, greatest in Northern Hemisphere summer during the 1962—66 period shown in fig. 5. Recent values of this same gradient measured from NIMBUS-III during 1969—70 fell within the range bars in all seasons and in both hemispheres except during Northern Hemisphere winter. This re-emphasizes the need for a continuing program of radiation budget measurement so that we may measure and study the full natural variation of the radiation gradient.

On the time scale of a specific season, one cannot expect a direct relation between the radiation gradient measured from satellites and the resulting atmospheric circulation. Whereas, this would be the case on Mars, our oceans and hydrologic cycle provide other means to release energy into the atmosphere and often operate out of phase with each other and with the radiative forcing from space.

Nevertheless, as an illustration of the potential equivalent variations of radiation gradient we have constructed the simple linear example shown in fig. 6. Here the mean summer and winter values of the thermal wind (V_T)[2]) are used with the corresponding mean values of radiation gradient index (from fig. 5) to derive the linear relation. Mean values of gradient measured over the southern hemisphere are noted by the arrows, they would indicate a lesser range of the mean V_T in that hemisphere. Shaded areas denote the range of measured gradient in all summers and winters and the equivalent range of circulation activity. Research now underway will study the actual physical and dynamical relations between the satellite measurement of radiation resulting from atmospheric conditions and the subsequent circulations forced, in part, by the radiative energy exchange. The grossly oversimplified illustration in fig. 6 serves as a reminder that this application of the satellite measurements can proceed in parallel with an increasingly polished description of "mean" conditions.

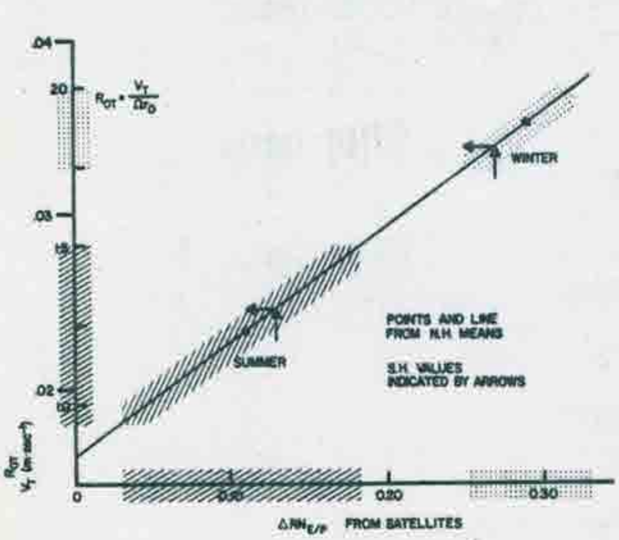
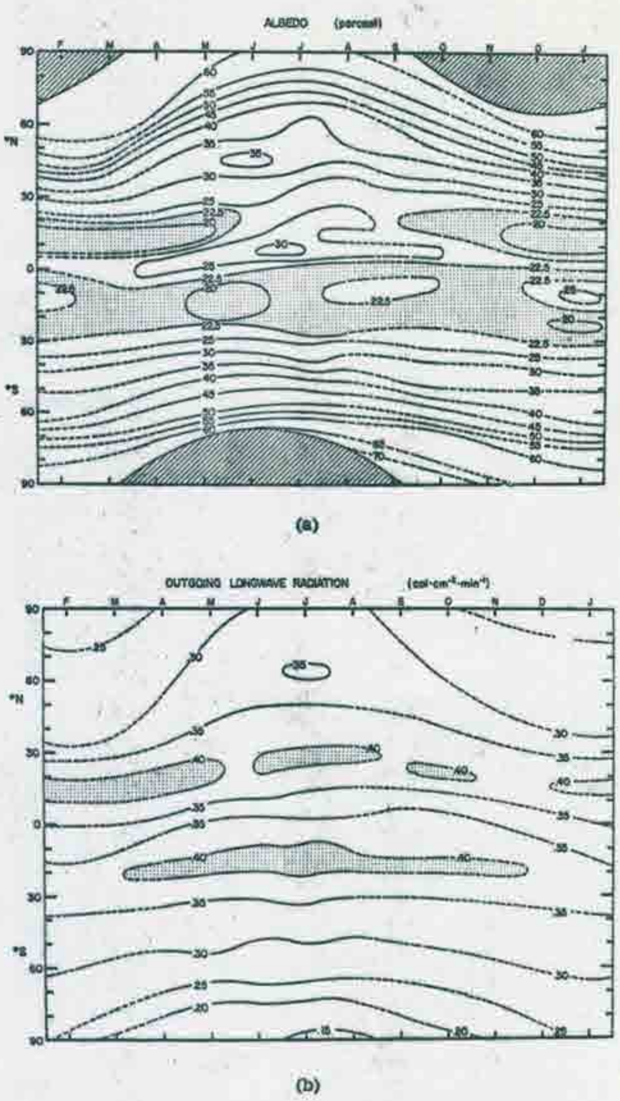


Fig. 6
Illustration noting the potential (indirect) relation between radiation gradient, as measured from satellites and the circulation of the atmosphere.



(a)

(b)

Fig. 7 a, 7 b
Time-latitude sections of (a) planetary albedo and (b) outgoing longwave (infrared) radiation, as measured from the Nimbus III satellite (after (9)). Fig. 7 c — see p.

4. High frequency time and space changes in the earth's radiation budget

This section is included to present the reader with examples of the radiation budget measurements from satellites on time and space scales sufficient to consider the local and regional energetics. The higher frequency data from the scanning radiometer is emphasized. Most results are recent ones from NIMBUS-III; they are described in detail in RASCHKE et al. (9).

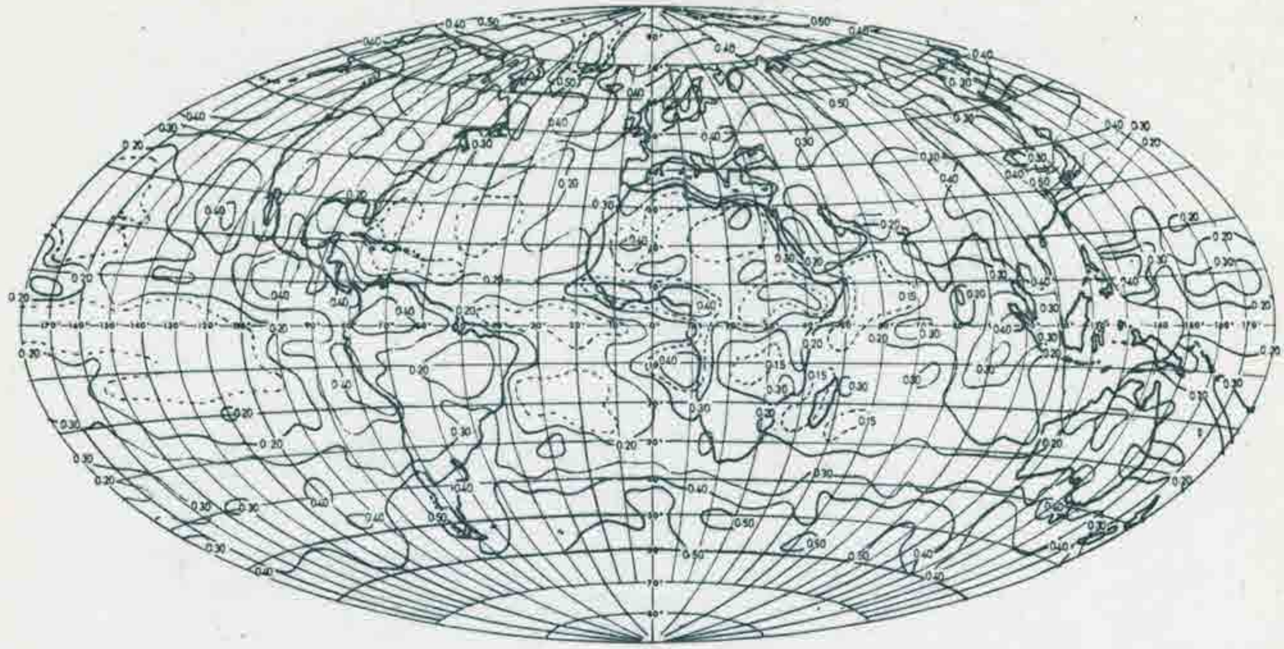
Figures 7a, 7b, and 7c denote time-latitude sections from pole-to-pole during April, 1969 — February 1970. They show the monthly course of outgoing infrared radiation, W_L; planetary albedo, A; and net radiation, Q_N, in each latitude zone.

Geographical variations of the same radiation measurements are shown for the period 1—15 July 1969 in the

[2]) Northern Hemisphere from 20°—70° N between the levels 1000 and 300 mb.

ALBEDO

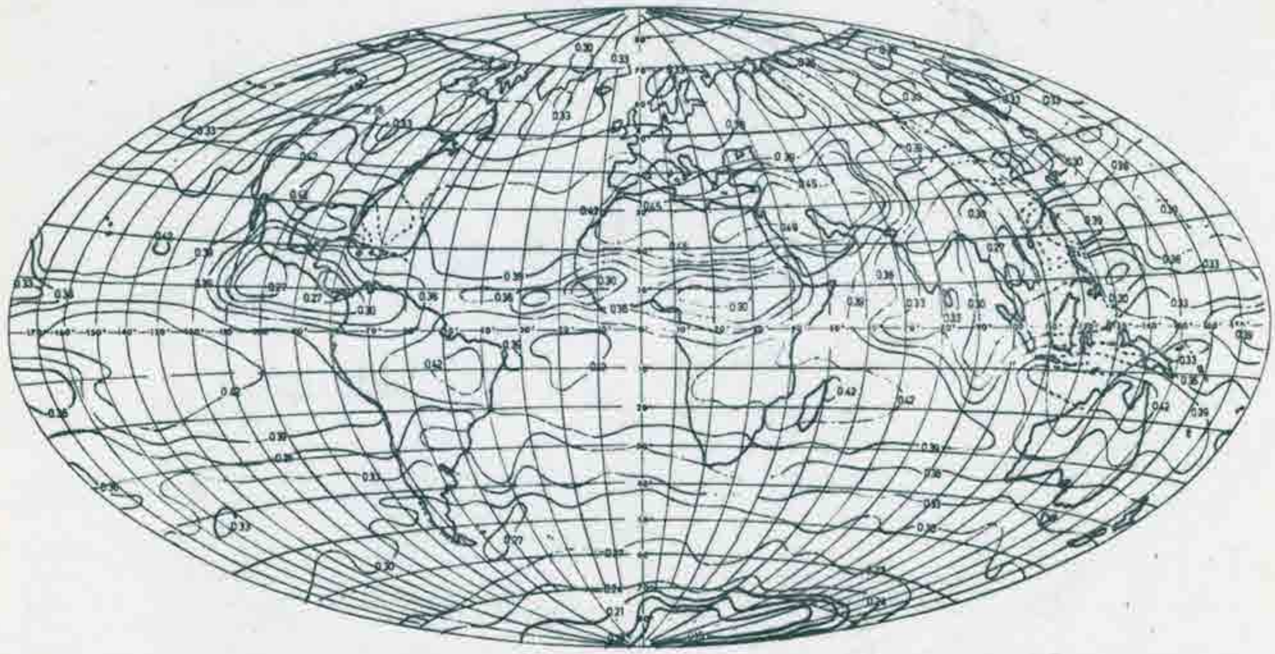
NIMBUS III: 1-15 JULY 1969



(a)

OUTGOING LONGWAVE RADIATION
(cal cm^{-2} min^{-1})

NIMBUS III: 1-15 JULY 1969



(b)

Fig. 8 a, 8 b
Maps of the geographical distribution of (a) planetary albedo and (b) outgoing longwave radiation, as measured during 1 — 15 July 1969 from the Nimbus III satellite (after (10)).
Fig. 8 c — see p.

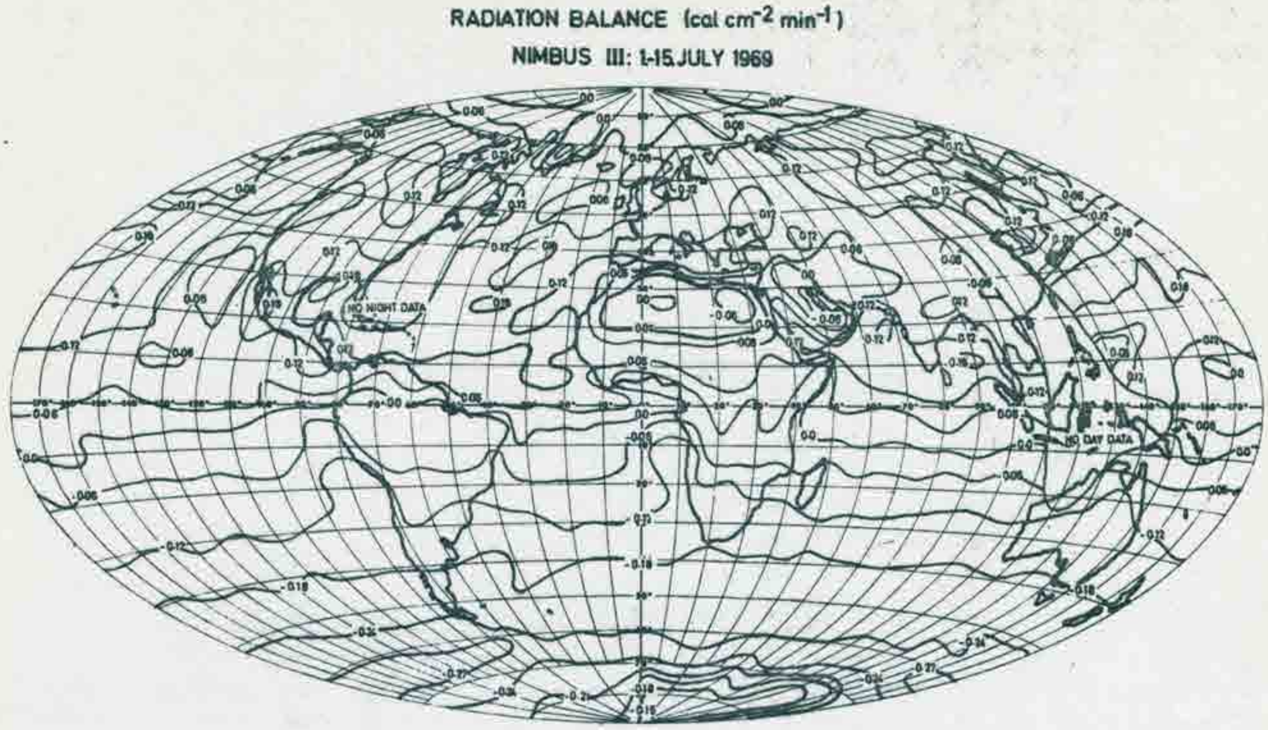


Fig. 8 c
Map of the geographical distribation of net radiation, as measured during 1 — 15 Juli 1969 from the Nimbus III satellite (after (10).

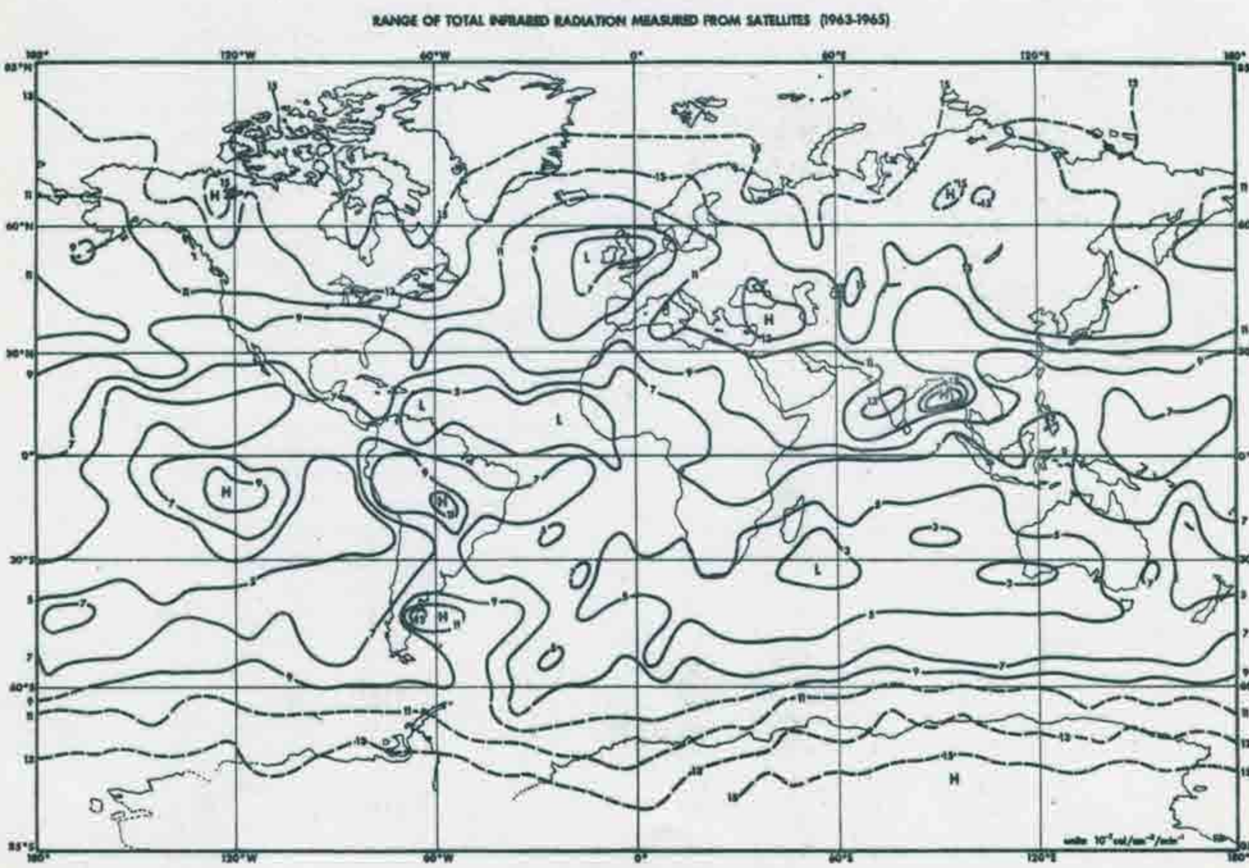


Fig. 9
Geographical variation of the range of mean seasonal infrared radiation lost to space as measured from the first generation meteorological satellites of the United States.

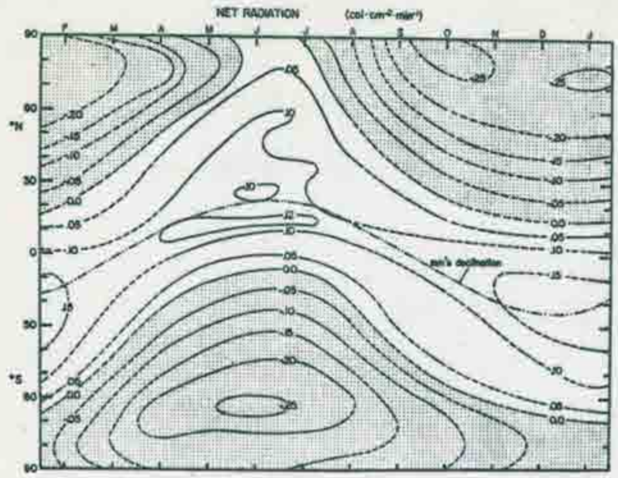


Fig. 7 c
Time-latitude section of net radiation, as measured from the Nimbus III satellite (after (9)).

set of fig. 8a, 8b and 8c. Here the high area resolution of the NIMBUS-III experiment can be used to examine radiation patterns characteristic of the tropical convergence zone, sub-tropical desert regions and special areas of cloudiness in mid-latitudes during these 15 days.

A final example of the geographical variation of radiation to space is seen in fig. 9. Based on measurements from nine seasons with the low area resolution Wisconsin sensors, we see here the natural range of the seasonal values of infrared emittance to space. As in the case of the interannual radiation gradients, more study of these results is now in order. Some features, such as the large range of values over the Indian monsoon sector, can be interpreted with little difficulty. Questions are posed, however, by the maxima of range in the tropical eastern Pacific and by the minima near the British Isles. The latter might be due to persistent cirriform cloudiness.

5. Summary

During the 1960's, radiation budget measurements from satellites have allowed quantitative study of the global energetics of our atmosphere-ocean system. A continuing program is planned, including independent measurement of the solar constant. Thus far, the measurements returned from two basically different types of satellite experiments are in agreement on the longterm global scales where they are most comparable. This fact, together with independent estimates of the accuracy of measurement from each system, shows that we now measure the energy exchange between earth and space better than it can be calculated.

Examples of application of the radiation budget data were shown. They can be related to the age-old problem of climate change, to the basic question of the thermal forcing of our circulation systems, and to the contemporary problems of local area energetics and computer modeling of the atmosphere.

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New Estimate of Annual Poleward Energy Transport by Northern Hemisphere Oceans

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ABSTRACT

Recent measurements of the earth's radiation budget from satellites, together with extensive atmospheric energy transport summaries based on rawinsonde data, allow a new estimate of the required poleward energy transport by Northern Hemisphere oceans for the mean annual case. In the region of maximum net northward energy transport (30–35N), the oceans transport 47% of the required energy (1.7×10^{23} cal year^{-1}). At 20N, the peak ocean transport accounts for 74% at that latitude; for the region 0–70N the ocean contribution averages 40%.

1. Introduction

Poleward energy transport by ocean currents plays an important role in climate on earth and has been a subject of study for many years. Bryan (1962) provides a synopsis of the estimates based on surface heat budget studies (Budyko, 1958; Albrecht, 1960; Sverdrup, 1957). In addition, he demonstrates a method for oceanic transport calculations based on hydrographic data as an extension of earlier work by Jung (1952). The inadequacies of the former method are shown by Bryan to result primarily from the fact that the transport is calculated as a small residual of two large quantities, the net radiation gain of the ocean surface and the net energy loss (to the atmosphere) due to latent and sensible heat exchange. Unfortunately, global availability of hydrographic data is probably not yet extensive enough to use the second technique for global ocean transport estimates; an additional difficulty is the ambiguity in the choice of reference level.

The present study uses a third, indirect approach based entirely upon measurements. Satellite data on the net radiation budget of the earth-atmosphere system (Vonder Haar and Suomi, 1971) are now available over sufficient time periods (data from the years 1962–70 are used in this study) to allow a firm estimate of the "mean annual" energy exchange between earth and space. In addition, rawinsonde data from the MIT General Circulation Library for the 5-year period May 1958 through April 1963 give a matching data set for which Oort (1971) has calculated the energy transport in the atmosphere.

2. Method of calculation

The energy balance for a polar cap north of a certain latitude ϕ (°N) can be written in the form (compare Starr, 1951)

$$\partial E/\partial t = \mathrm{AT}+\mathrm{OT}+\mathrm{RF}+\mathrm{HF}, \tag{1}$$

where

$\partial E/\partial t$ rate of change with time of the total energy in a polar cap north of latitude ϕ (°N). The important components of the total energy are the internal energy, potential energy, latent heat, and kinetic energy of the atmosphere, ocean and cryosphere (snow and ice) contained in the polar cap.

AT atmospheric energy flux into polar cap across latitude ϕ(°N) (area S1)

$$=\int_{S1}\int \rho(c_vT+gz+Lq+c^2/2+p/\rho)v\,dx\,dz$$

OT oceanic energy flux into polar cap across latitude ϕ(°N) (area S2)

$$=\int_{S2}\int \rho(c_v'T+gz+c^2/2+p/\rho)v\,dx\,dz$$

RF net radiational flux into polar cap at top of the atmosphere (area S3)

$$=\int_{S3}\int Q\,dx\,dy$$

HF energy flux into polar cap at the surface of the solid earth (area S4)

$$=\int_{S4}\int Q'\,dx\,dy$$

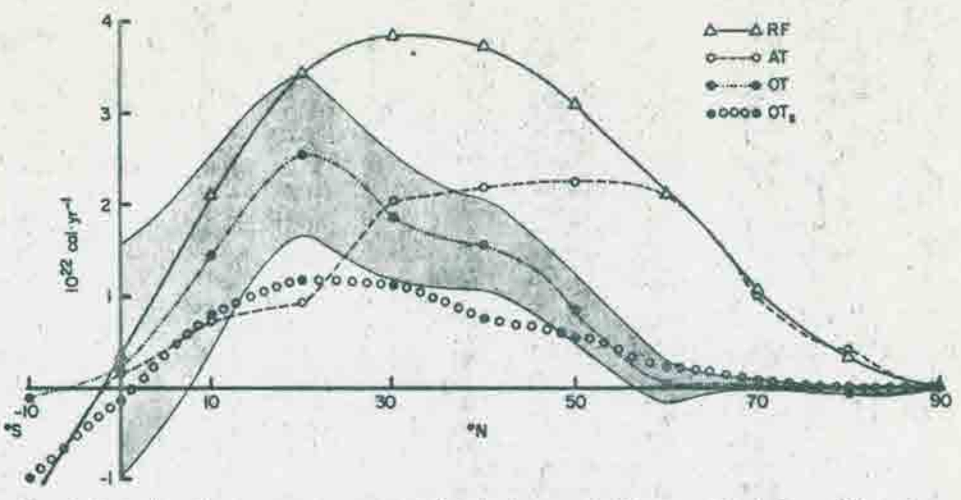

FIG. 1. Variation of net energy transport with latitude over the Northern Hemisphere: RF, total required energy transport inferred from satellite measurements; AT, measured energy transport by the atmosphere; OT, ocean energy transport derived from the present study; OT$_s$, ocean energy transport according to Sellers (1965). Uncertainty in the OT values is denoted by the shading. Minus values indicate net transport to the south.

Other symbols used are:

c	wind (current) velocity
$c_v(c_v')$	specific heat at constant volume in atmosphere (ocean)
g	acceleration resulting from gravity
L	heat of condensation
p	pressure
q	specific humidity
Q	net flux of radiation at top of atmosphere
Q'	net flux of energy at surface of solid earth
T	temperature
v	northward component of wind (current)
z	height
ρ	density

For a period of a year the energy storage[1] in the atmosphere-ocean-cryosphere system ($\partial E/\partial t$) and the energy exchange with the solid earth (HF) are probably small compared to the remaining terms on the right-hand side of (1) and will be neglected. Thus, on a mean annual basis we assume an approximate balance of the form

$$\mathrm{AT}+\mathrm{OT}+\mathrm{RF}=0. \qquad (2)$$

From satellite measurements we have an estimate of the net radiational heating (RF) which under the assumptions used in deriving (2) must be equal to the net northward energy flow into the polar cap. The atmospheric measurements supply an estimate of AT. Therefore, the oceanic transport (OT) can be computed from (2) as a residual. Fig. 1 shows the total energy flux from radiation requirements, the atmospheric flux, and the deduced oceanic flux as a function of latitude. The numerical values are presented in Table 1. Sellers' (1965) values for atmospheric (AT$_s$) and oceanic (OT$_s$) transports based on the most recent surface energy budget estimates [including Budyko's (1963) estimates] are also tabulated.

[1] Variability in ocean energy storage, presently under study in terms of temperature anomalies, is not well known but most probably lies within the error limits of this study.

3. Error estimates

The atmospheric energy flux was computed for five different years. This enabled us to estimate the error of the 5-year mean value of AT by calculating the standard deviation of the mean, $S=\sigma(X)/(N-1)^{\frac{1}{2}}$, where $n=5$. Twice the standard deviation of the mean indicates the 95% confidence limit and we assume that the instru-

TABLE 1. Poleward energy transport in the Northern Hemisphere for the mean annual case: units ($\times 10^{22}$ cal year^{-1}); minus indicates net southward transport.

Latitude	RF*	AT†	OT	AT$_s$‡	OT$_s$‡	OT/RF (%)
90N	0	0	0	0	0	—
80N	0.32	0.37	−0.05	0.25	0	—
70N	1.14	1.10	0.04	1.18	0.09	3.5
60N	2.15	2.11	0.04	2.14	0.26	2
50N	3.10	2.24	0.86	2.82	0.57	28
40N	3.76	2.20	1.56	3.10	0.79	41
30N	3.88	2.03	1.85	2.60	1.15	48
20N	3.49	0.91	2.58	1.34	1.19	74
10N	2.14	0.72	1.42	0.42	0.81	66
EQ	0.33	0.13	0.20	−0.07	−0.16	60
10S	−1.54	−1.44	−0.10	−0.66	−1.00	6.5

* The values of RF are slightly different from those reported by Vonder Haar and Suomi (1971), since the measurements from the 13 seasons of that study have been augmented by 4 more measurement seasons (see Vonder Haar, 1972).

† The values of AT are slightly different from those reported earlier by Oort (1971). The present values represent the mean of 5 years analyzed separately. In the earlier study the same 5-year data set was analyzed but as one sample.

‡ Values of AT and OT as given by Sellers (1965).

ment plus sampling error of the atmospheric transport is not larger than this value. Error estimates are given in Table 2. From Vonder Haar (1968) and Vonder Haar and Suomi (1971), error analysis of the satellite measurements showed a maximum probable bias error of ±0.01 cal cm^{-2} min^{-1} in mean annual zonal values of the net radiation Q. The cumulative effect of such an error in the required transport (RF) values derived from the satellite measurements increases equatorward from the beginning point of integration at $\phi = 90$N (Table 2). The law of propagation of independent errors was used to obtain the estimate of error in the derived ocean transport $E_{OT} = (E^2_{RF} + E^2_{AT})^{\frac{1}{2}}$. This error[2] is indicated by the shading in Fig. 1.

TABLE 2. Probable error in measurements and estimates of poleward energy transport in the Northern Hemisphere for the mean annual case: units (10^{22} cal year^{-1}).

Latitude	E_{RF}	E_{AT}	E_{OT}
90N	—	—	—
80N	±0.02	±0.12	±0.12
70N	±0.08	±0.06	±0.10
60N	±0.18	±0.10	±0.21
50N	±0.32	±0.16	±0.34
40N	±0.48	±0.10	±0.49
30N	±0.67	±0.16	±0.68
20N	±0.88	±0.08	±0.88
10N	±1.10	±0.12	±1.10
EQ	±1.33	±0.10	±1.33
10S	±1.56	±0.24	±1.58

4. Discussion of results

Between 10–50N the ocean transports derived in the present study are significantly greater than those previously derived. In the region of maximum net northward energy transport by the ocean-atmosphere system (30–35N), the ocean transports 47% of the required energy (1.7×10^{22} cal year^{-1}). At 20N, the peak ocean transport accounts for 74%; for the region 0–70N the ocean contribution averages 40%. Both the absolute magnitude of the ocean transport and the relative role of the oceans significantly exceed earlier estimates.

The total transport value (RF) derived directly from satellite measurements is also greater than earlier (pre-satellite) estimates (Houghton, 1954). Vonder Haar (1968) pointed out that the increased required energy transport stemmed primarily from a lower albedo in tropical regions than was estimated before satellite data became available. Vonder Haar and Hanson (1969) showed that the increased net gain of energy in the tropics was corroborated by the few available measurements of direct solar energy reaching the tropical ocean surfaces. In fact, they showed that the extra energy entering the tropical zones was primarily absorbed in the oceans. Independent checks of the satellite values (1962–66) on the annual scale have just recently been possible using Nimbus 3 radiation budget measurements during 1969–70 (Vonder Haar *et al.*, 1972; Raschke *et al.*, 1972). These data, from a totally different radiometer system, confirm the earlier satellite results of a lower planetary albedo (0.29–0.30), an increased net energy gain, and an increased required transport. In addition, the atmospheric transport values used in this study are somewhat smaller than earlier values compiled by Sellers (see Table 1). Thus, the absolute value of the ocean transport must be greater since the overall requirement is greater and the atmosphere transports less.

These new ocean values show that not only the absolute amount, but also the relative role of the oceans, are greater than previously believed. They are shown to transport on the average 40% of the total required. Peak net transport values for the ocean (20N) apparently exceed the flat atmospheric maxima between 30–50N. Location of the ocean peak is the same as that shown by Sellers, but the transport value is more than 50% larger. Note that the curves indicate the need for a small net northward energy transport across the equator by the oceans.

In recent years large numerical models have been used to simulate the circulation of the atmosphere and the ocean. As they pass from the development phase they offer great promise for numerical experimentation. A measure of their representativeness is gained by comparison of their computed values of basic circulation parameters with the observed values. Comparison of the recent values of ocean transport computed in a joint ocean-atmosphere model run for the annual case (Bryan, 1969; Manabe, 1969) shows that the total Northern Hemisphere transport calculated by the model is less than the results of this study (but in agreement with previously accepted values). Furthermore, the latitude of maximum transport by oceans was calculated in the model to be about 38N, which is not in agreement with our results or any others. Wetherald and Manabe (1972) have recently run another joint atmosphere-ocean model in which seasonal variations of insolation were allowed. Reduced snow cover in the high-latitude summer lessened the annual gradient of net radiation to space and also the meridional transport of energy by ocean currents. Thus, this recent experiment caused the ocean value to deviate even further from our result. At this point it should be mentioned that the models presently used to simulate the combined atmosphere-ocean system are highly idealized and cannot be expected to give very reliable results for the ocean transport. For example, in the model horizontal sub-grid scale and vertical mixing strongly affect the oceanic

[2] The error shown for the tropics and subtropics results primarily from the cumulative satellite error. It is definitely a worst-case estimate for this region since independent information [Vonder Haar and Suomi (1971) from measurements; London and Sasamori (1971) from calculations] show no *net* energy transport required across the equator. Thus, our transport integration could begin at 0° rather than 90°.

heat transport. Unfortunately, it is not known what value one should use for the mixing coefficient.

In summary, the estimates of ocean transport obtained in the present study are greater than previously believed, are derived from two new extensive data sets that have been checked and will be continuously updated in the years to come, and are timely in view of the renewed interest in the influence of the ocean on weather and climate. Our results suggest that air-sea interaction in mid-latitudes may be even more significant than presently acknowledged.

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