Zonal Average Earth Radiation Budget measurements from Satellites for Climate Studies

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ABSTRACT

Data from 29 months of satellite radiation budget measurements, taken intermittently over the period 1964 through 1971, are composited into mean month, season and annual zonally averaged meridional profiles. Individual months, which comprise the 29 month set, were selected as representing the best available total flux data for compositing into large scale statistics for climate studies. A discussion of spatial resolution of the measurements along with an error analysis, including both the uncertainty and standard error of the mean, are presented.

ACKNOWLEDGEMENTS

We thank the many scientists and engineers who contributed to the success of the satellite experiments. Professor Verner Suomi's personal research and dedication to the goal of measuring the earth's radiation budget inspired all of us.

We also acknowledge the Atmospheric and Hydrospheric Applications Division of NASA Goddard Space Flight Center for sponsoring the preparation of this report under NGR 06-002-102.

1.0 INTRODUCTION

A climatology of the net flux of energy exchanged between Planet Earth and space has been computed from radiance and irradiance measurements taken by Earth orbiting satellites. The net flux is derived as a difference between total spectral incoming solar flux and the sum of separate measurements of reflected shortwave and thermal infrared exitance. This relationship is shown mathematically as:

$$\text{Net} = \text{Solar In} - \text{Reflected} - \text{Thermal}$$

Net, reflected, and infrared flux are frequently referred to as radiation budget data or measurements in this report.

Radiation budget measurements are presented in the form of mean month, season, and annual zonal profiles. Zonal averaged data are also referred to as mean meridional profiles. The terminology zonal averaged, is to be interpreted as an average taken over 360 degrees of longitude for any given latitude zone.

Mean zonal radiation budget profiles are presented as climate statistics for use in climate studies. The authors believe that the profiles for the period 1964 through 1971 are the best statistics available to date. Future measurements from the Earth Radiation Budget (ERB) experiment on Nimbus 6 and Nimbus G satellites will augment this data set.

There have been a number of requests from persons involved in climate research for such statistics. This report will provide them with the statistics and, at the same time, provide a source of information about satellite radiation budget measurements with appropriate references for those desiring additional detailed information.

2.0 DATA COLLECTION

Mean zonal radiation budget profiles are made up from a collection of 29 individual monthly sets. This collection does not correspond on a one-to-one basis with the collection of an earlier publication by Vonder Haar and Ellis (1974), which emphasized maps of data or with the mean set of Vonder Haar and Suomi (1971), which did not contain data from the early seventies. The collection in this report is shown in Table 1. It includes additional data from the ITOS 1 and NOAA 1 satellites (Flanders and Smith, 1975) during early 1970 and 1971, and ESSA 7 data (Mac Donald, 1970) in late 1968 and early 1969. Data excluded from this report, yet useful for other purposes, are the TIROS 4 and 7 satellite measurements in 1962 through 1964 along with 8 months of experimental satellite measurements. The TIROS satellite could not sample poleward of the 63.5 latitudes because of their orbital inclination (Bandeen, et al., 1965). Limited on board tape recorder storage left data gaps between some ground readout stations. The sampling deficiencies precluded obtaining representative monthly data.

Measurements from experimental satellites for April through November 1965 showed large differences between them and the 29 months of remaining measurements. Globally averaged albedoes dropped from 28.5 percent in March 1965 to 19.5 percent in August 1965. Albedo over North Africa was in the neighborhood of 10 percent for the months of May, June, July and August 1965. These are extremely low values and thus it seems quite reasonable that the data do not represent true absolute values. Thus, they were not included in the 29 month data zonal average data set.

TABLE 1.

Chronological list of earth-orbiting satellites from which the present radiation measurements were taken. The approximate local time at which each satellite crossed the equator during daylight hours is given in parentheses. EX = Experimental, N2 = Nimbus 2, N3 = Nimbus 3, E7 = ESSA 7, I1 = ITOS 1 and N01 = NOAA 1.

	YEAR								
MONTH	1964	1965	1966	1967	1968	1969	1970	1971	SAMPLE SIZE
Jan		EX (10:30)				E7 (14:30)	N3 (11:30)		3
Feb		EX (10:35)				E7 (14:30)			2
Mar		EX (10:40)				E7 (14:30)			2
Apr						N3 (11:30)	I1 (15:00)		2
May			N2 (11:30)			N3 (11:30)	I1 (15:00)	N01 (15:00)	4
Jun			N2 (11:30)			N3 (11:30)	I1 (15:00)		3
Jul	EX (08:30)		N2 (11:30)			N3 (11:30)			3
Aug	EX (08:55)					N3 (11:30)			2
Sep	EX (09:15)								1
Oct	EX (09:40)				E7 (14:30)	N3 (11:30)			3
Nov	EX (10:05)				E7 (14:30)				2
Dec	EX (10:30)				E7 (14:30)				2
ANNUAL	6	3	3	0	3	9	4	1	29

About the Averages

Occasionally a near polar zonally averaged albedo was estimated. A criterion applied in computing albedo was that if more than 1 watt per square meter of incoming solar flux fell into a latitude zone, then there should be a reflected flux. Whenever this criterion was not satisfied, an estimated albedo was assigned to the zone. The criterion was not satisfied in a few low illumination cases in latitude zones bordering the polar night. Here the satellite measured a very small signal in the visible light spectrum, a signal not significantly above noise in the satellite system.

Values which were estimated are shown in Table 2. Estimated albedoes for these low light cases provide a better input to the net flux calculation than an assignment of zero to albedo or reflected flux. The most severe case for which an assignment was made is September at 75 north latitude. An assignment of 50 percent albedo gave a 73 watts/m^2 reflected flux. If this estimate is off by ± 5 units out of 100 or ± 8 watts/m^2, then it is near the uncertainty in the measurements (discussed in Section III). Again this is an extreme case but, there is little doubt that an estimated value allows a more representative calculation of net flux to space than would be obtained by calling a missing albedo zero.

Estimated albedos were not carried through in computing annual average albedo. Since measured albedoes are available for many months of the data, there is doubt as to whether estimated values would add to the representativeness of annual average albedo. However, estimates were included in computing mean season albedo at 65 and 75 south latitudes in the June-July-August season, and at 85 north latitude in the

TABLE 2

ESTIMATED ALBEDO VALUES
FOR LOW INSOLATION CONDITIONS

Month	Latitude	Albedo (Percent)	Reflected Flux Density (Watts/m^2)
June	-65	50	2
July	-65	50	6
August	-65	50	28
	-75	50	4
September	85	56	49
	75	50	73
	-75	60	50
	-85	64	13
<u>Season</u>			
June, July, August	-75	50	12
	-65	50	1
September, October, November	85	56	16

September-October-November season. It was necessary to use estimates in these seasons since all months in the seasons had missing albedoes at such latitudes.

About the Spatial Resolution

Resolution of both the measurement and the grid map must be considered. Two types of sensor measurements comprise this data set: scanning radiometers and wide angle or flat plate disc sensors.

The scanning radiometers are medium resolution radiometers (MRIR) on board Nimbus 2 and 3 satellites. The field of view of the radiometers varies from 50 km of great circle arc distance at nadir to 110 km at an angle of 40^{0} from nadir (Raschke and Bandeen, 1970).

All remaining satellite measurements comprising this data set are from flat plate disc sensors with a field of view of 180^{0} or 2π steradians of solid angle. The solid angle subtended by the Earth at the satellite is a function of satellite height only. Thus the spatial resolution of a flat plate sensor is dependent on height alone. This resolution varies from 53^{0} of great circle arc (5,900 km) for lower orbiting experimental satellites to 70^{0} (7,770 km) for higher orbiting ESSA, ITOS, NOAA satellites.

If only total power received at the sensor is considered, one may be mislead as to measurement resolution of a flat plate sensor. By considering a smaller area on the earth's surface contributing to 50 percent power on the sensor one may get a better estimate of sensor resolution. A great circle arc distance on the Earth's surface contributing to 50 percent of the power incident on a sensor can be calculated if one assumes the Earth atmosphere system to be a homogeneous, isotropic reflector and emitter (Appendix A). Half power resolution in terms of great circle arc of the Earth's surface is 11.5^{o} (1,280 km) for the lower orbiting satellite to 19^{o} (2, 130 km) for the higher orbiting satellites. Thus, the half power area is only 5 to 10 percent of the full power area or approximately 25 percent of the great circle arc.

All of the data are presented at 10^{o} latitude intervals from 85N to 85S in this report. Data from higher resolution scanning radiometers were averaged over each 10^{o} latitude zone. If half power resolution of the flat plate sensors is considered to be an estimate of sensor measurement resolution, then it is seen that the experimental data are compatible with 10^{o} gridding. However, ESSA, ITOS, and NOAA data, which comprise just 10 monhts of our 29 month data set, are much smoother and more representative of flux measurements over 20^{o} latitude bands. Users of mean statistics presented here should be aware of the flux measurement resolution. The numbers and graphs should be considered as representing fluxes from 10 to 20^{o} latitude zones.

Flat plate data have been reduced from satellite height (hs) to some reference height above the Earth's surface (ho). The ho values vary from 30 km for experimental satellites, 0 km for ESSA 7, and 10 km for ITOS 1 and NOAA 1; the difference over 0 to 30 km has less than a 1 percent effect on the reduced flux value. It must be kept in mind that a reduction to some ho is not a deconvolution process which considers inhomogeneously distributed radiation sources in the sensor field of view. Instead, homogeniety and isotropy are assumed so that simple geometry allow a reduction. It must be noted that a sensor does measure significant anisotropic radiance outside the geometrically reduced field of view. The reduction is not too bad when working with time averaged data since transient cloud patterns tend to promote a homogeneous target. However, there are certain standing inhomogenities present in time average fluxes (primarily due to ice-snow fields, continent-ocean distribution, and stationary cloud systems) which preclude simple geometric data reduction to an arbitrary reference level, ho.

3.0 ERROR ANALYSIS OF THE MERIDIONAL PROFILES

Uncertainty of individual samples can be combined into an uncertainty of the mean value. Additionally, standard deviation in net flux values can be computed for each monthly time period from which a standard error of the mean can be calculated. A comparison between computed uncertainties and error in the mean estimates allows one to draw some conclusions concerning natural time variability about the mean.

Uncertainty in the Mean

Measurement and data reduction uncertainties are not always well known. Each uncertainty is considered qualitatively, at least, as being composed of random and systematic errors. The uncertainty due to random errors can be minimized by sampling frequently in both space and time. Systematic errors, if known in sign and magnitude, can be removed from the data. However, some are not known and, therefore, cannot be removed. Individual identifiable, but not necessarily quantitative, uncertainties are discussed as follows.

1) The "solar constant" has been taken as 1360 w/m^2 after Drummond et al.(1968). A total uncertainty in the solar constant is estimated to be $\pm$ 1.5 percent after Thekaekara (1975).
2) Calibration of sensors and traceability of the calibration to primary standards.

3) Unaccountable degradation of the sensor in space.

4) Diurnal sampling bias since all of data are taken from sun synchronous satellites, i.e., satellites which sample at the same local sun time each day. Thus, the effects of diurnal cloud variations are not measured.

5) Smoothing in space by flat plate sensors so that a grided value represents a measurement for some larger area than the grid spacing. This was discussed in the previous section on resolution.

6) Corrections applied to MRIR scanners on Nimbus 2 and 3 to account for anisotropic Earth-atmosphere reflections to space.

7) Parameterization applied to Nimbus 3 longwave spectral radiances along with limb darkening parameterization applied to both Nimbus 2 and Nimbus 3 MRIR to obtain total longwave flux to space.

8) An assumption of zero net planetary radiation balance applied in ESSA 7 data reduction necessary to resolve reflected fluxes to space. This assumption becomes less restrictive for longer time averaging intervals. Absolute error in net radiation may be as large as $\pm$ 10 watts/m^2 when averaged over a month for ESSA 7 data.

9) All monthly sets have time sampling voids so that a monthly mean sample is not quite a true mean. Some monthly samples have spatial sampling voids caused by inadequate onboard tape recorder storage between satellite ground readout sites. Others are due to low signal-to-noise ratio in low light situations near the solar terminator on the Earth.

10) Natural year-to-year variability of the target which might preclude the mean of a few monthly samples being a representative estimate of a climate mean.

Conservative estimates of the total uncertainty in incoming solar, albedo and infrared exitance are as follow:

Solar insolation:	σ	$= \pm$ 1.5 percent
Albedo:	σ	$= \pm$ 5 percent ($\pm$ 0.05 x Albedo)
Infrared Exitance:	σ	$= \pm$ 5 percent

Uncertainty in the solar constant of ± 1.5 percent is from Thekaekara (1975). Uncertainty of ± 5 percent in albedo and infrared exitance is quite conservative when one considers just uncertainty in sensor calibration and degradation which is 2 to 3 percent. However, if we consider all of the uncertainties in our list, then ± 5 percent is not too rigid.

Uncertainty in net radiation has been computed considering effects of both dependent and independent errors (Appendix B). Tables 3 and 4 show the computed uncertainties for mean months, mean seasons, and mean annual net radiation. The very large uncertainties in September are due to having just one monthly data set to apply as a mean September. The large September uncertainty is not so outstanding in mean season uncertainties. Total uncertainty for the mean annual case is less than or equal to 10 watts/m^2 at all latitudes. This is not too bad when one considers that 1/2 of all the uncertainty or 5 watts/m^2 is equivalent to the uncertainty in the global average solar constant. In other words, 10 watts/m^2 uncertainty in net flux is equivalent to a 3 percent uncertainty in the value of the solar constant if exact Earth flux measurements could be made.

TABLE 3

Uncertainty in Mean Monthly Net Radiation (watts/meter^2)

Latitude	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
North 85	4	5	7	8	8	11	12	14	8	5	6	5
75	5	8	8	9	8	10	11	13	9	9	6	6
65	8	8	7	9	8	9	9	9	10	7	9	8
55	6	9	8	9	7	9	9	10	11	8	10	9
45	7	8	8	10	7	9	9	10	13	7	11	10
35	7	9	9	10	8	9	9	11	14	8	9	8
25	8	10	10	11	8	9	9	11	15	8	10	9
15	8	10	10	11	8	9	8	10	14	8	10	10
5	8	10	10	11	7	8	8	10	14	8	10	10
South 5	8	10	10	10	7	9	8	10	15	9	10	10
15	9	10	10	11	8	9	9	11	15	9	11	11
25	9	10	10	10	7	8	8	10	15	9	11	11
35	9	10	10	10	7	7	7	9	13	8	11	11
45	9	10	9	9	6	7	8	8	12	8	10	11
55	9	10	9	8	5	10	7	10	11	7	11	11
65	9	10	8	7	10	5	5	6	9	7	11	12
75	10	10	7	9	4	4	4	4	5	6	12	14
85	10	14	9	6	4	4	3	4	4	7	12	14

TABLE 4

Uncertainty in Mean Seasonal and Mean Annual Net Radiation (watts/meter^2)

Latitude	DJF	MAM	JJA	SON	ANNUAL
North 85	5	8	12	6	8
75	6	8	12	7	9
65	8	8	9	9	9
55	8	8	9	10	9
45	8	9	9	11	9
35	8	9	10	11	10
25	9	10	10	11	10
15	10	10	9	11	10
5	10	9	9	11	10
South 5	10	9	9	12	10
15	10	10	9	12	10
25	10	9	9	12	10
35	10	9	8	11	10
45	10	8	7	10	9
55	10	8	9	10	9
65	10	8	5	9	8
75	11	7	4	8	8
85	13	6	4	8	8

Standard Error in the Mean

Standard error in the mean is an estimate drawn from independent random samples of how "good" the mean value is. Standard error in the mean is defined as:

$$SEM = \frac{\sigma}{N}$$

where σ is the standard deviation and N is the number of samples in the mean. A sufficient number of monthly radiation budget samples are not available to compute SEM on a monthly basis. However, by combining monthly into seasonal σ's, a meaningful statistic can be generated. The process of combination is identical to that for combining uncertainties (Appendix C). The results in Table 5 show that SEM of the polar regions is larger in the fall and winter seasons of each hemisphere than is the uncertainty in mean statistics of Table 4. Just the opposite, and of lesser extent, is seen in the tropics. The large SEM in polar regions indicates that large year-to-year variations are in the data in polar regions (70 to 90 latitude), which are larger than the uncertainty in the data. They most probably are real interannual variations. But, one should have less confidence in mean values in near polar regions because of large standard error in the mean, particularly during the fall and winter seasons.

TABLE 5

Standard Error of Season Mean and Annual Mean Net Radiation (watts/meter^2)

Latitude	DJF	MAM	JJA	SON	ANNUAL
North 85	13	4	8	12	10
75	11	6	10	9	9
65	9	10	11	3	9
55	7	9	9	3	7
45	7	7	6	4	6
35	7	7	4	2	5
25	7	7	4	2	5
15	6	9	4	2	6
5	5	9	6	2	6
South 5	6	10	6	1	7
15	7	8	4	2	6
25	7	9	6	4	7
35	6	10	6	4	7
45	5	8	7	4	6
55	5	7	6	3	5
65	7	8	8	5	7
75	4	9	10	8	8
85	2	14	11	9	10

4.0 MEAN RADIATION BUDGET STATISTICS

The statistics are presented so that 12 mean months are followed by four mean seasons and a mean annual set. An average value is tabulated for each 10 degree latitude zone in watts/meter^2 except for albedo which is in percent. Solar input to the Earth atmosphere system was specified with correct Earth-Sun geometry using a solar constant of 1360 watts/meter^2.

Column headings are defined as follows:

NET: net radiotive flux exchange with space

IR: infrared exitance, or thermal longwave flux loss to space

ALB: Albedo in percent

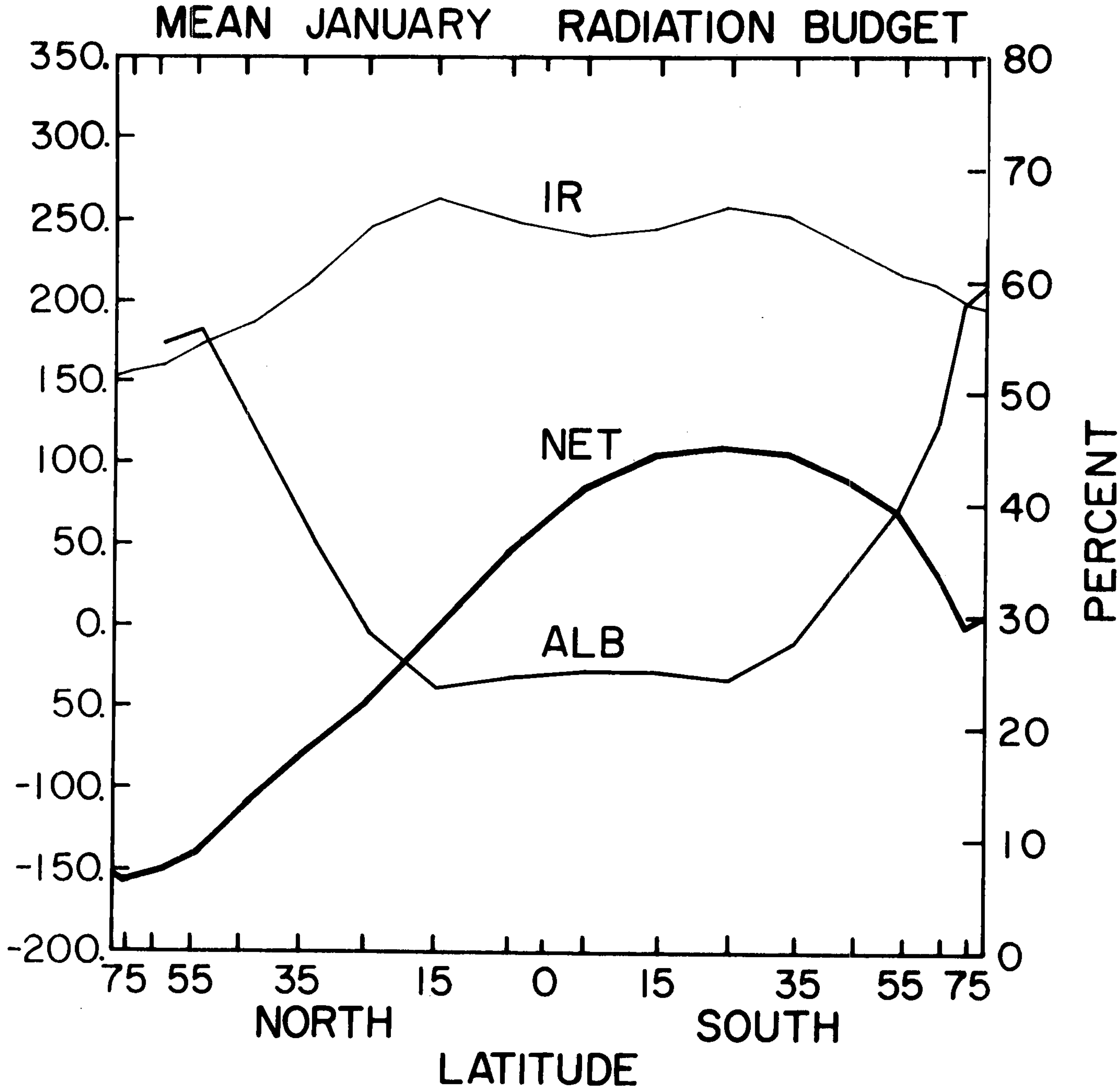
ABS: Shortwave or solar flux absorbed in an Earth-atmosphere column.

REF: reflected and scattered shortwave, or solar flux to space.

Each mean set of zonal statistics is followed by a graphical presentation of zonal average albedo, infrared exitance and net radiation.

MEAN JANUARY RADIATION BUDGET (watts/meter^2)

LAT	NET	IR	ALB	ABS	REF
85	-153.2	153.2	0.0	0.0	0.0
75	-156.9	156.9	0.0	0.0	0.0
65	-155.6	162.0	54.6	6.4	7.7
55	-143.7	175.3	55.9	31.6	40.1
45	-114.2	188.0	47.6	73.8	67.1
35	-82.2	213.6	37.9	131.4	80.2
25	-50.0	249.4	28.5	199.4	79.5
15	-4.4	266.6	23.1	262.2	78.8
5	45.8	253.4	24.2	299.2	95.5
-5	85.2	244.8	24.7	330.0	108.2
-15	105.8	248.7	24.6	354.5	115.7
-25	110.7	262.2	23.9	372.9	117.1
-35	106.4	255.7	27.2	362.1	135.3
-45	89.1	237.1	33.9	326.2	167.3
-55	68.6	221.1	39.7	289.7	190.7
-65	32.8	213.8	47.1	246.7	219.6
-75	.4	202.0	58.0	202.4	279.5
-85	4.3	196.9	59.5	201.2	295.6



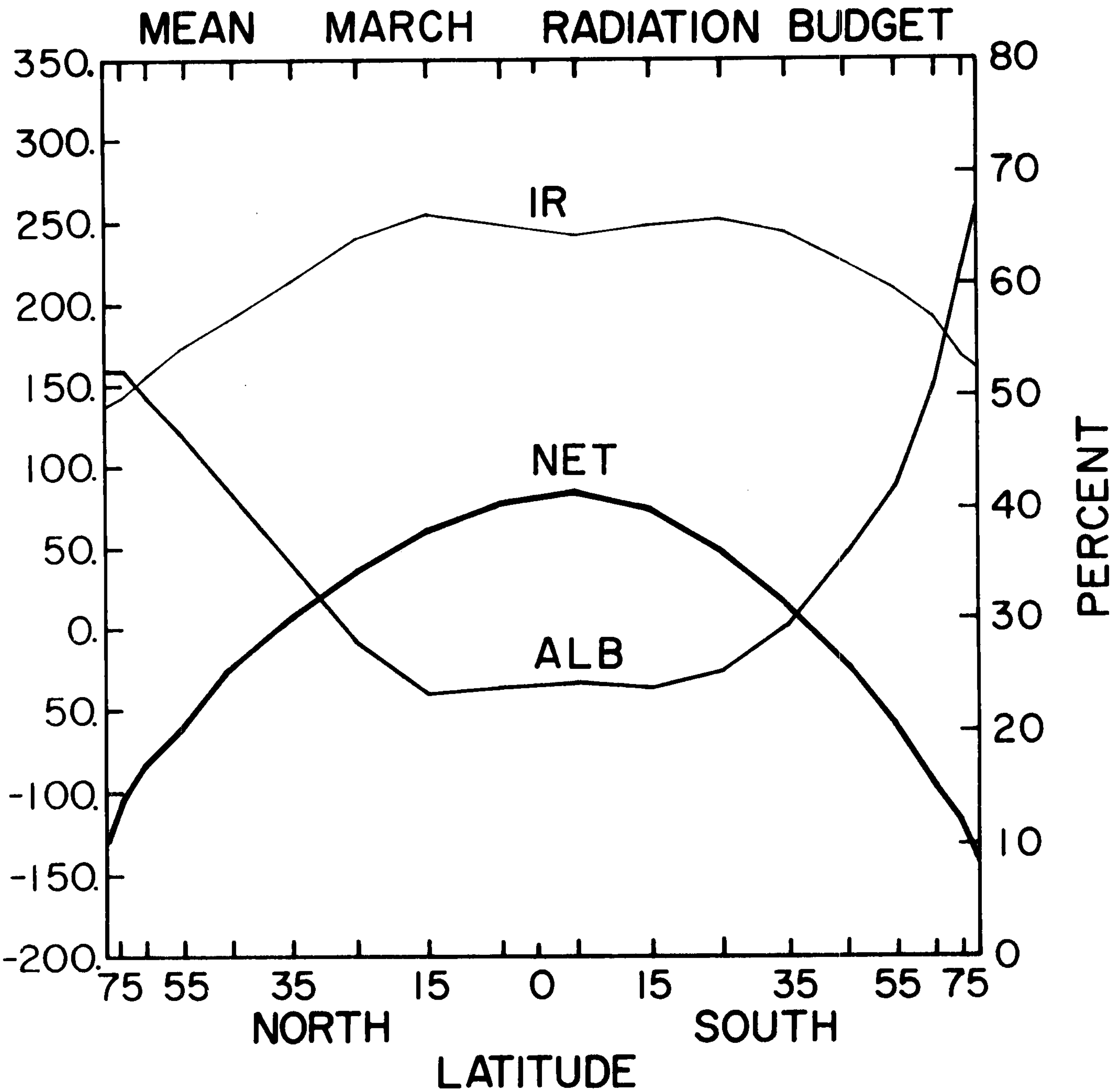
MEAN JANUARY RADIATION BUDGET
350.
300.
250.
200.
150.
100.
50.
0.
50.
-100.
-150.
-200.
watts / m⁻²
80
70
60
50
40
30
20
10
0
PERCENT
IR
NET
ALB
75 55 35 15 0 15 35 55 75
NORTH
SOUTH
LATITUDE

MEAN FEBRUARY RADIATION BUDGET (WATTS/METER^2)

LAT	NET	IR	ALB	ABS	REF
85	-148.2	148.2	0.0	0.0	0.0
75	-145.2	149.9	51.3	4.7	5.0
65	-130.5	161.4	52.3	31.0	33.9
55	-101.5	174.0	45.8	72.4	61.2
45	-75.7	190.7	43.3	115.0	87.9
35	-46.4	215.5	37.1	169.1	99.7
25	-13.0	244.1	29.4	231.1	96.2
15	23.7	261.5	24.4	285.2	92.0
5	59.1	256.6	24.2	315.7	100.8
-5	85.8	248.3	24.7	334.0	109.6
-15	96.8	251.4	24.0	348.2	109.9
-25	89.1	257.0	24.7	346.1	113.5
-35	66.2	252.8	28.8	318.9	129.0
-45	37.9	237.4	35.1	275.3	148.9
-55	4.4	222.1	41.9	226.5	163.3
-65	-37.2	208.5	50.8	171.3	176.9
-75	-66.1	191.8	59.7	125.7	186.2
-85	-73.9	188.6	63.2	114.8	197.1

MEAN MARCH RADIATION BUDGET (WATTS/METER^2)

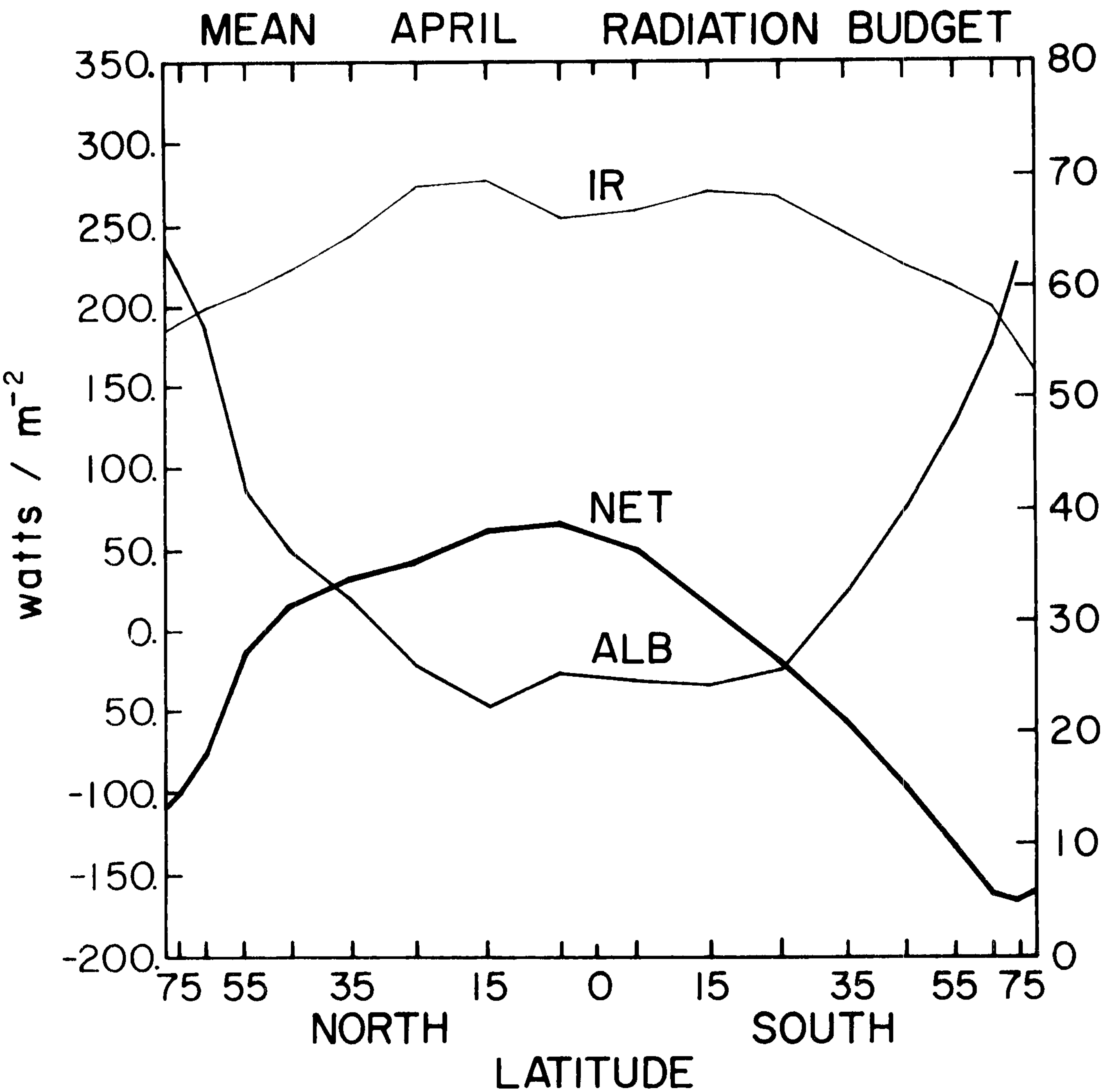
LAT	NET	IR	ALB	ABS	REF
85	-129.1	142.6	52.6	13.5	15.0
75	-102.1	146.4	52.6	44.3	49.2
65	-78.3	161.4	49.5	83.1	81.5
55	-55.7	181.0	45.9	125.2	106.2
45	-22.8	196.0	40.7	173.2	118.8
35	6.9	218.6	34.4	225.5	118.3
25	34.7	244.8	27.4	279.5	105.5
15	60.5	259.1	23.0	319.6	95.5
5	78.0	252.4	23.6	330.4	102.1
-5	85.4	246.2	24.0	331.6	104.7
-15	74.7	252.4	23.5	327.1	100.5
-25	48.5	255.9	24.9	304.4	100.9
-35	15.8	247.9	29.0	263.7	107.7
-45	-19.0	230.5	35.1	211.5	114.4
-55	-55.2	214.1	41.4	158.9	112.3
-65	-93.4	196.3	50.6	102.9	105.4
-75	-116.6	171.9	60.5	55.3	84.7
-85	-137.5	163.5	66.0	26.0	50.5



MEAN MARCH RADIATION BUDGET
350.
300.
250.
200.
150.
100.
50.
0.
50.
-100.
-150.
-200.
watts / m^-2
80
70
60
50
40
30
20
10
0
PERCENT
IR
NET
ALB
75 55 35 15 0 15 35 55 75
NORTH
SOUTH
LATITUDE

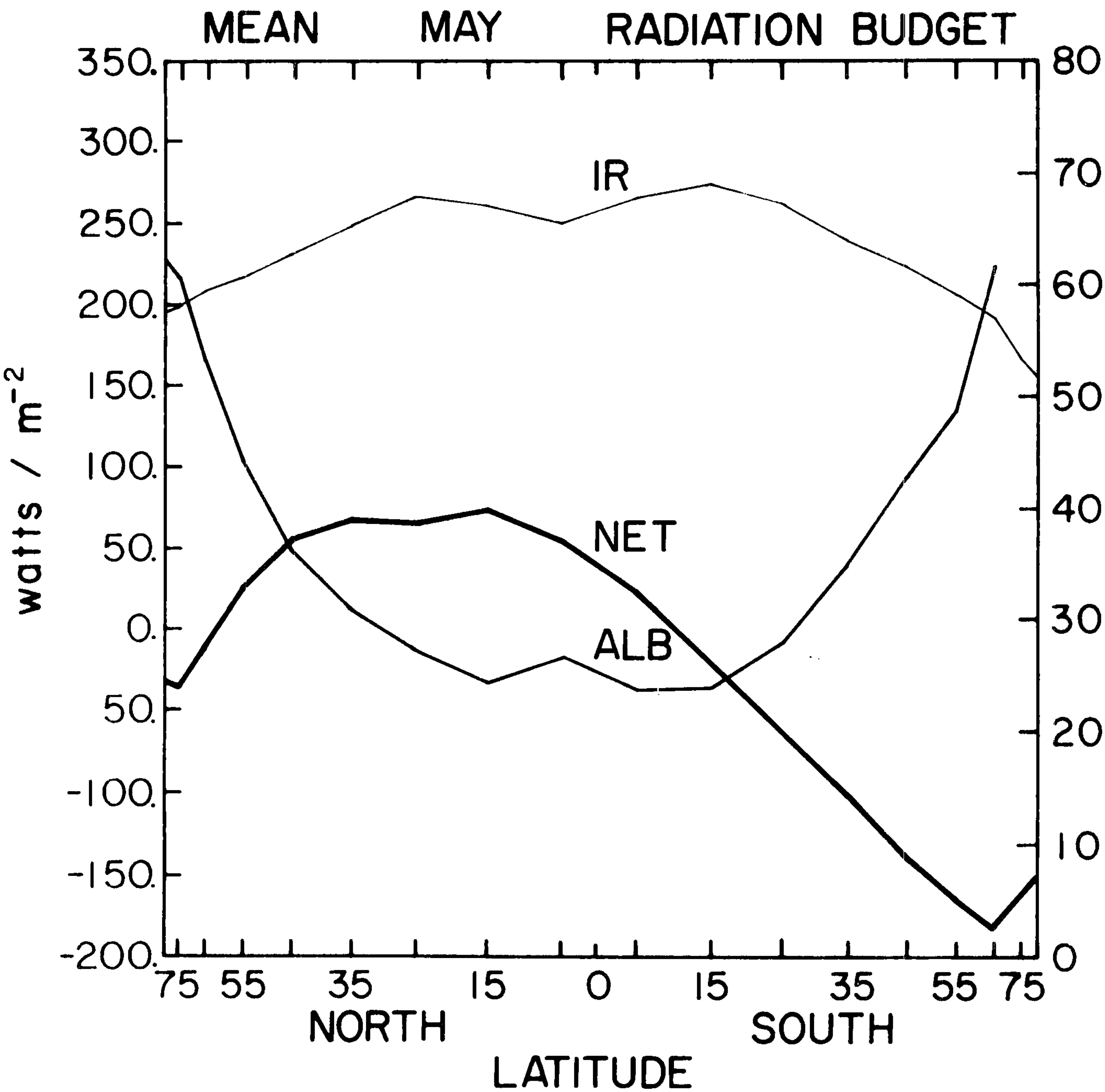
MEAN APRIL RADIATION BUDGET (WATTS/METER^2)

LAT	NET	IR	ALB	ABS	REF
85	-107.1	190.0	63.0	83.0	141.3
75	-97.4	194.6	60.2	97.1	146.9
65	-72.5	203.6	55.4	131.1	162.8
55	-12.5	212.7	41.6	200.2	142.6
45	20.1	228.0	35.3	248.1	135.4
35	33.9	248.9	31.6	282.9	130.7
25	42.5	270.6	25.5	322.2	110.3
15	60.9	281.4	21.9	342.3	96.0
5	64.8	258.0	25.1	322.8	108.2
-5	49.3	261.8	24.4	311.2	100.4
-15	14.2	274.7	23.9	288.9	90.7
-25	-19.1	270.9	25.3	251.8	85.3
-35	-56.0	249.6	32.0	193.6	91.1
-45	-95.5	231.2	39.5	135.6	88.6
-55	-132.6	216.5	47.0	83.9	74.4
-65	-162.5	203.6	54.3	41.2	48.9
-75	-168.7	178.9	62.0	10.1	16.5
-85	-166.0	166.0	0.0	0.0	0.0


MEAN APRIL RADIATION BUDGET
350.
300.
250.
200.
150.
100.
50.
0.
50.
-100.
-150.
-200.
watts / m^{-2}
80
70
60
50
40
30
20
10
0
PERCENT
IR
NET
ALB
75 55 35 15 0 15 35 55 75
NORTH
SOUTH
LATITUDE

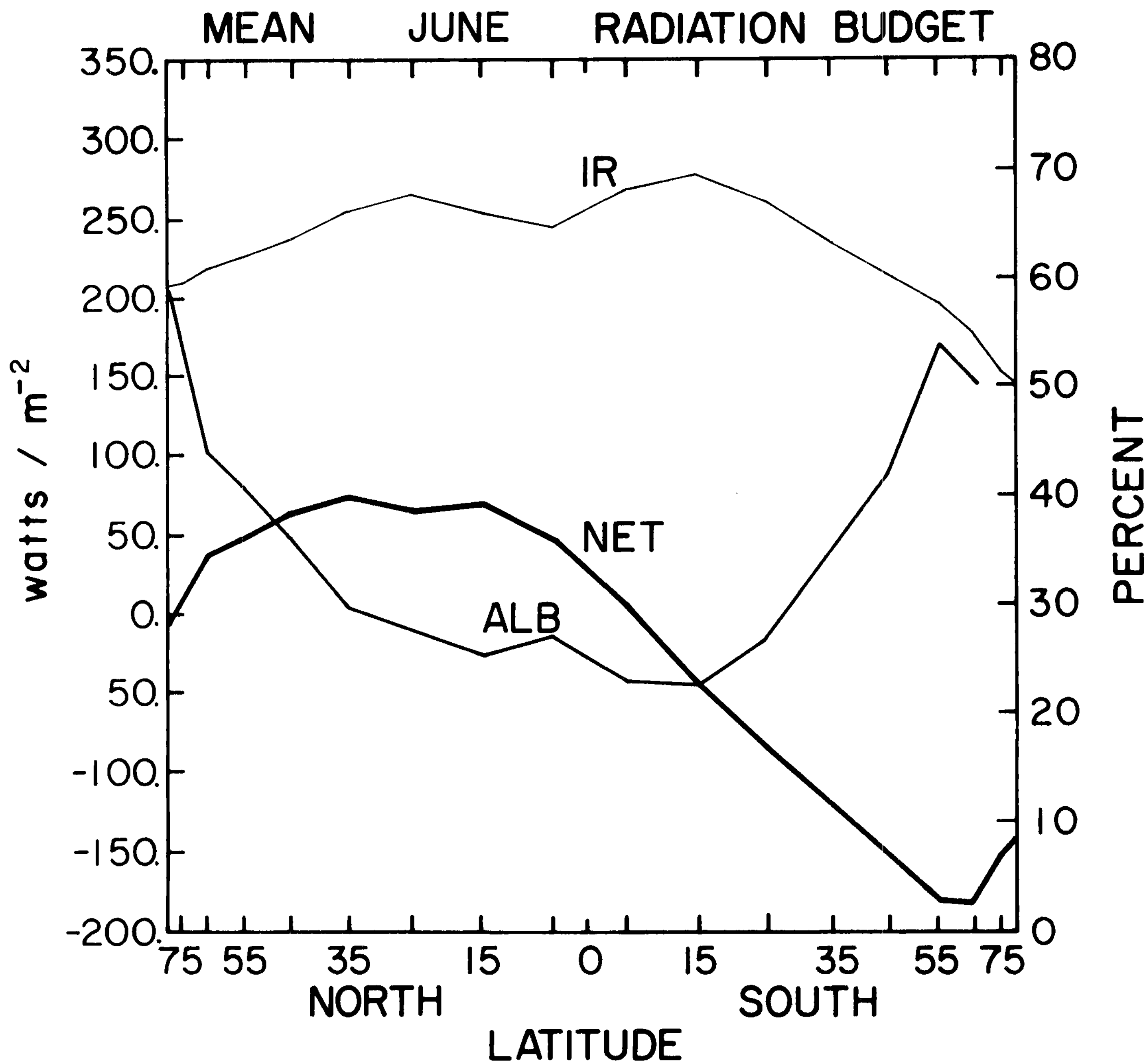
MEAN MAY RADIATION BUDGET (WATTS/METER^2)

LAT	NET	IR	ALB	ABS	REF
85	-35.8	197.5	62.0	161.8	263.9
75	-39.1	202.1	60.5	163.0	249.6
65	-11.5	213.4	50.9	201.9	209.3
55	29.7	221.4	42.0	251.1	181.8
45	57.4	235.7	35.0	293.0	157.8
35	68.5	252.6	30.2	321.1	138.9
25	66.2	270.0	26.6	308.4	109.5
15	73.5	264.5	23.8	338.0	105.6
5	54.9	253.5	26.2	308.4	109.5
-5	22.6	269.7	23.2	292.3	88.3
-15	-22.3	277.9	23.3	255.5	77.6
-25	-64.9	266.0	27.5	201.2	76.3
-35	-103.4	244.2	34.5	140.8	74.2
-45	-142.5	227.9	42.6	85.3	63.3
-55	-168.9	211.5	48.6	42.6	40.2
-65	-185.9	194.9	62.0	9.0	14.7
-75	-166.8	166.8	0.0	0.0	0.0
-85	-156.4	156.4	0.0	0.0	0.0


MEAN MAY RADIATION BUDGET
350.
300.
250.
200.
150.
100.
50.
0.
50.
-100.
-150.
-200.
watts / m⁻²
80
70
60
50
40
30
20
10
0
PERCENT
IR
NET
ALB
75 55 35 15 0 15 35 55 75
NORTH
SOUTH
LATITUDE

MEAN JUNE RADIATION BUDGET (WATTS/METER^2)

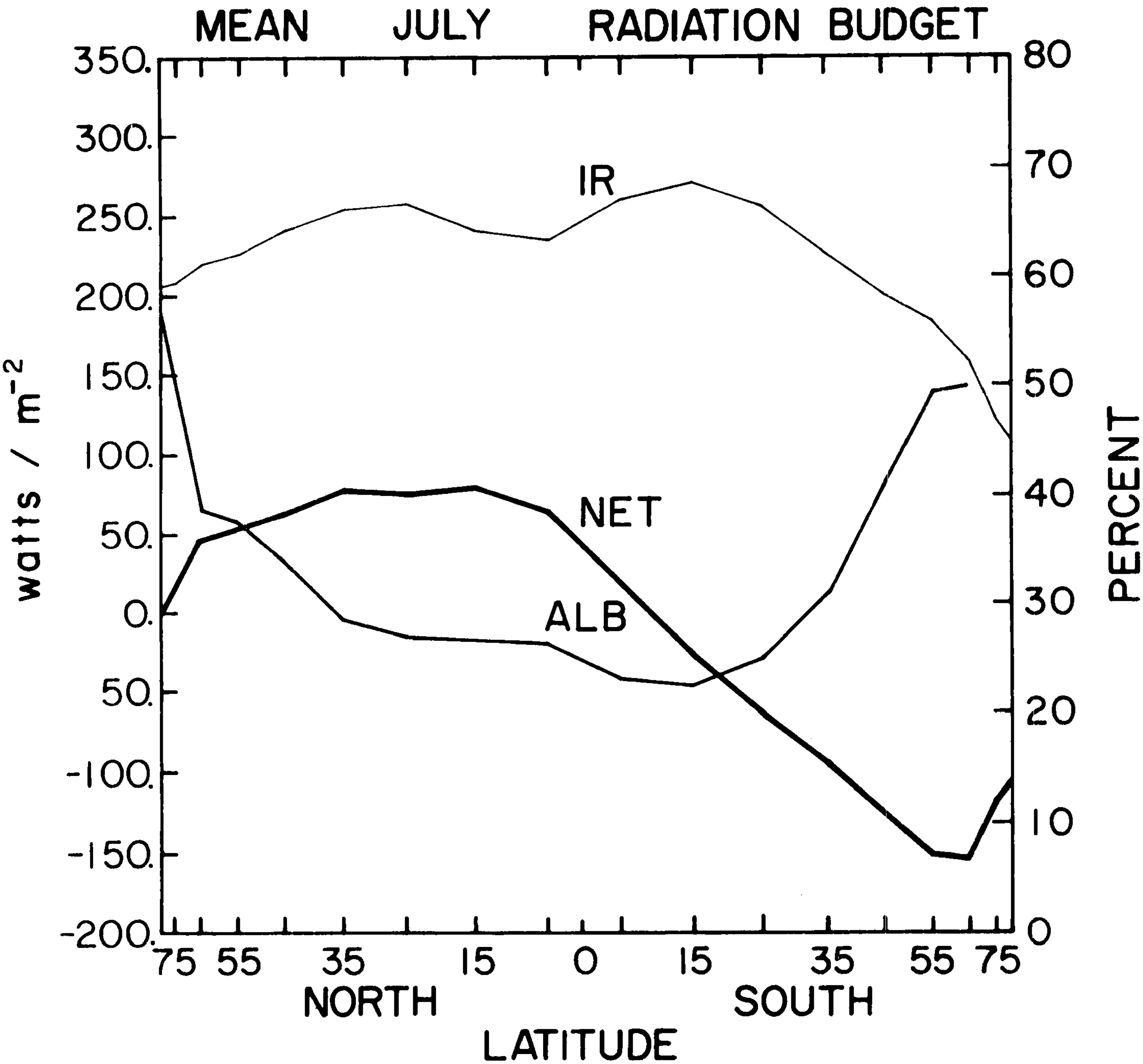
LAT	NET	IR	ALB	ABS	REF
85	-3.4	212.2	59.4	208.8	305.5
75	11.2	214.1	54.8	225.2	273.1
65	41.7	224.8	43.5	266.5	205.2
55	52.3	231.7	40.2	284.1	191.0
45	67.9	242.0	35.5	309.8	170.5
35	77.9	260.8	29.2	338.7	139.7
25	67.9	270.8	27.3	338.7	127.2
15	72.0	258.7	25.2	330.7	111.4
5	47.9	249.4	27.0	297.3	110.0
-5	6.1	273.6	22.8	279.6	82.6
-15	-44.0	283.4	22.4	239.4	69.1
-25	-85.5	266.8	26.7	181.4	66.1
-35	-121.1	240.3	34.5	119.3	62.8
-45	-152.4	219.9	41.7	67.5	48.3
-55	-178.9	202.9	54.0	24.1	28.2
-65	-181.5	183.4	50.0	1.9	1.9
-75	-153.4	153.4	0.0	0.0	0.0
-85	-143.9	143.9	0.0	0.0	0.0



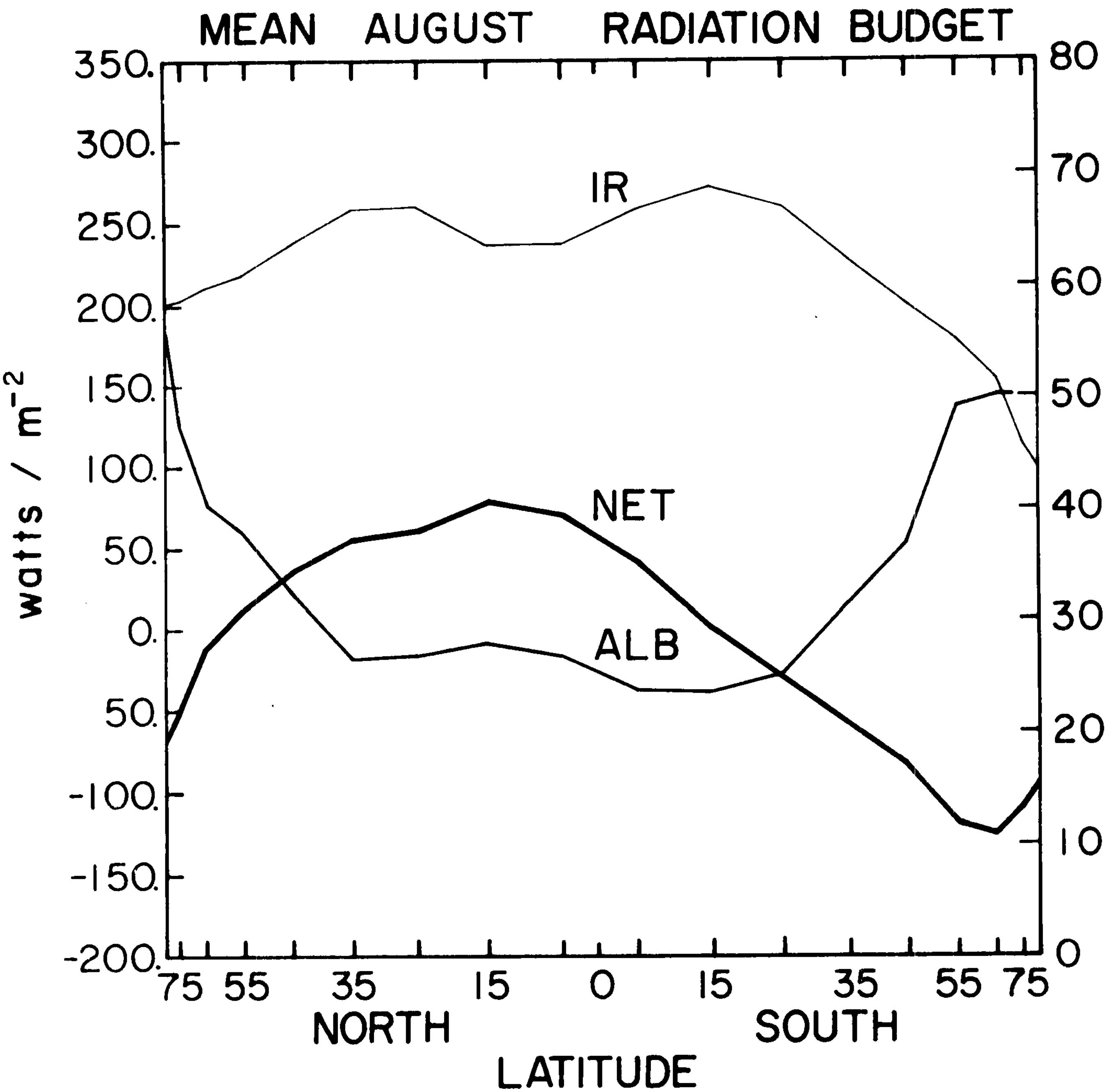
MEAN JUNE RADIATION BUDGET
350.
300.
250.
200.
150.
100.
50.
0.
50.
-100.
-150.
-200.
watts / m-2
80
70
60
50
40
30
20
10
0
PERCENT
IR
NET
ALB
75 55 35 15 0 15 35 55 75
NORTH
SOUTH
LATITUDE

MEAN JULY RADIATION BUDGET (WATTS/METER^2)

LAT	NET	IR	ALB	ABS	REF
85	1.0	206.9	56.1	207.9	265.7
75	18.3	209.7	50.4	227.9	231.6
65	48.4	223.4	38.6	271.8	170.8
55	55.2	229.2	37.4	284.4	169.9
45	64.7	246.2	33.2	310.9	154.5
35	78.9	259.2	27.8	338.1	130.2
25	76.3	261.7	26.6	338.0	122.5
15	80.5	243.8	26.4	324.3	116.3
5	64.4	238.7	26.1	303.1	107.1
-5	18.9	265.2	22.9	284.1	84.4
-15	-28.3	275.4	22.2	247.2	70.5
-25	-65.4	260.8	24.7	195.5	64.1
-35	-95.7	231.5	30.6	135.8	59.9
-45	-128.6	205.0	40.9	76.4	52.9
-55	-154.6	187.4	49.5	32.8	32.1
-65	-157.1	162.9	50.0	5.8	5.8
-75	-123.9	123.9	0.0	0.0	0.0
-85	-111.1	111.1	0.0	0.0	0.0



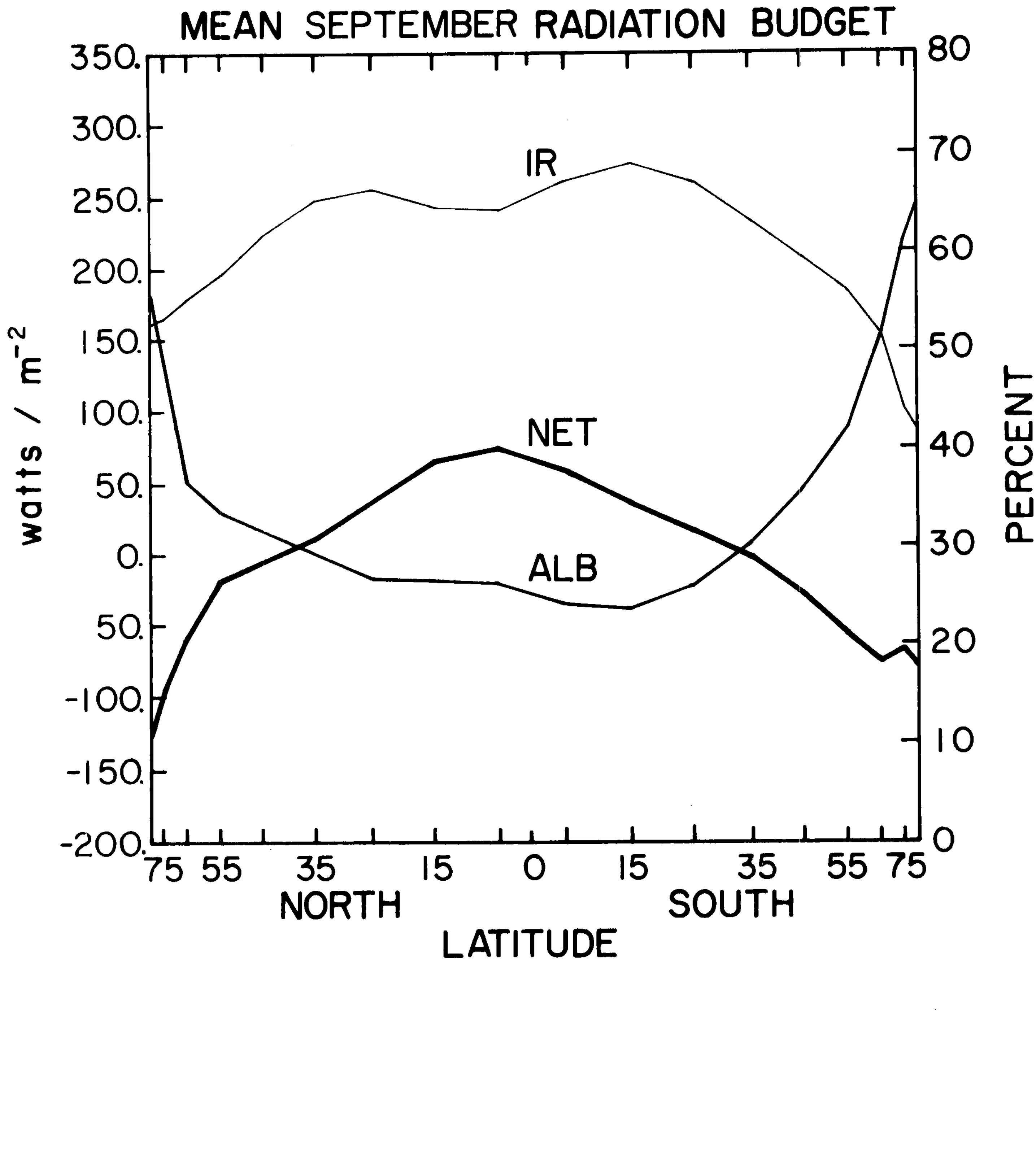
MEAN JULY RADIATION BUDGET
350.
300.
250.
200.
150.
100.
50.
0.
50.
-100.
-150.
-200.
watts / m⁻²
80
70
60
50
40
30
20
10
0
PERCENT
IR
NET
ALB
75 55 35 15 0 15 35 55 75
NORTH
SOUTH
LATITUDE



MEAN AUGUST RADIATION BUDGET
watts / m⁻²
PERCENT
IR
NET
ALB
350.
300.
250.
200.
150.
100.
50.
0.
50.
-100.
-150.
-200.
80
70
60
50
40
30
20
10
0
75 55 35 15 0 15 35 55 75
NORTH
SOUTH
LATITUDE

MEAN SEPTEMBER RADIATION BUDGET (WATTS/METER^2)

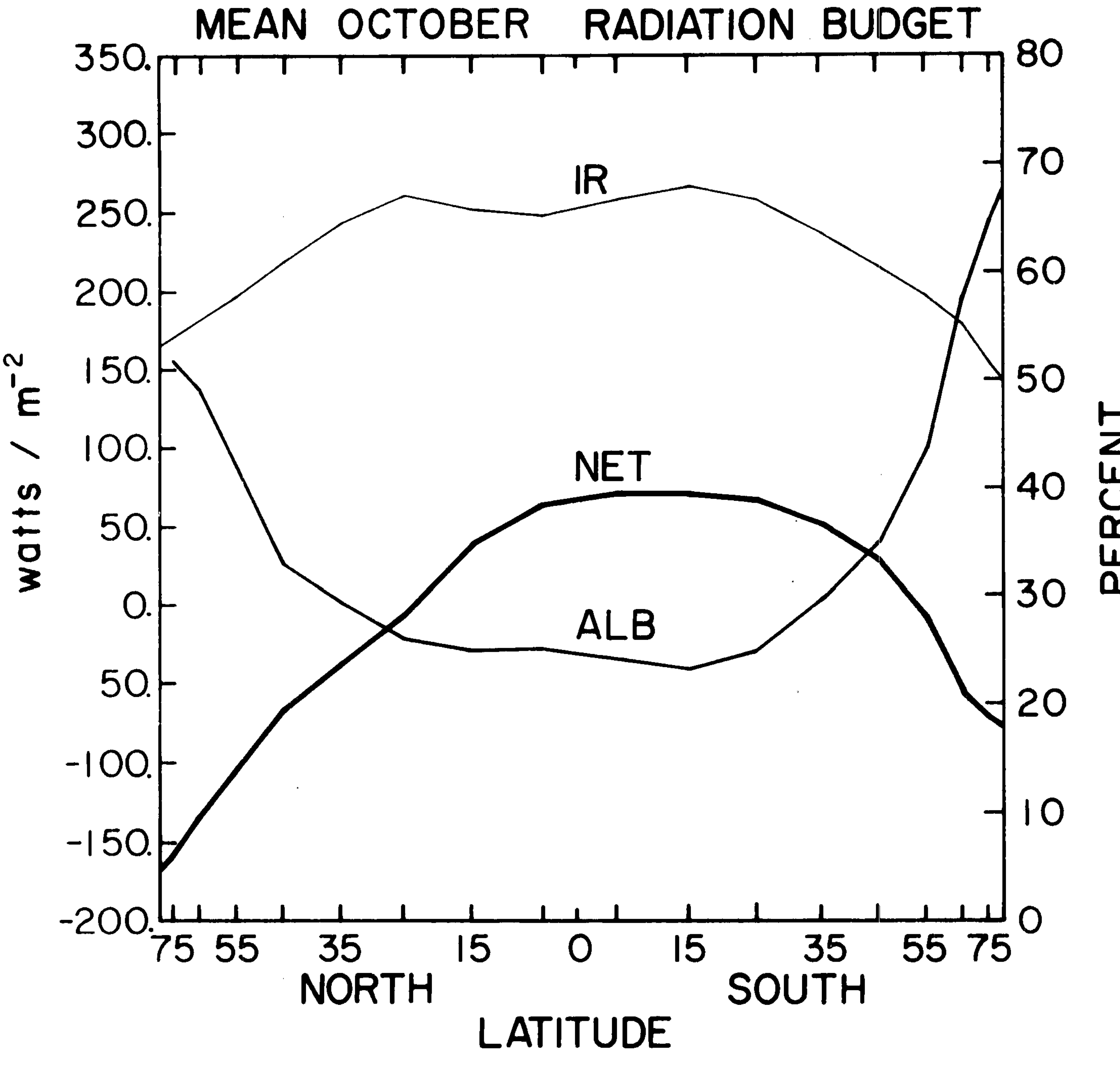
LAT	NET	IR	ALB	ABS	REF
85	-125.5	163.9	56.0	38.4	48.8
75	-95.0	169.5	49.6	74.1	73.3
65	-50.3	184.8	37.0	134.5	79.0
55	-18.2	201.5	33.1	183.4	90.7
45	-4.9	229.4	31.2	224.6	101.8
35	11.3	251.0	29.0	262.3	107.2
25	36.8	258.7	26.4	295.5	106.0
15	65.5	245.5	26.2	310.9	110.4
5	73.9	244.1	25.8	318.0	110.6
-5	58.3	264.3	23.7	322.6	100.2
-15	34.4	276.1	23.1	310.6	93.3
-25	14.9	263.6	25.4	278.5	94.8
-35	-4.6	237.8	29.6	233.2	98.0
-45	-30.4	212.0	35.0	181.6	97.8
-55	-57.5	186.9	40.9	129.4	89.5
-65	-78.6	154.1	50.5	75.5	77.0
-75	-67.3	100.4	60.0	33.1	49.7
-85	-77.6	85.1	64.0	7.5	13.3



MEAN SEPTEMBER RADIATION BUDGET
350.
300.
250.
200.
150.
100.
50.
0.
50.
-100.
-150.
-200.
watts / m^{-2}
80
70
60
50
40
30
20
10
0
PERCENT
IR
NET
ALB
75 55 35 15 0 15 35 55 75
NORTH
SOUTH
LATITUDE

MEAN OCTOBER RADIATION BUDGET (WATTS/METER^2)

LAT	NET	IR	ALB	ABS	REF
85	-168.5	169.0	0.0	.5	0.0
75	-158.6	174.6	51.5	16.0	17.0
65	-134.8	185.3	48.9	50.5	48.3
55	-103.8	201.3	42.0	97.5	70.6
45	-65.2	222.9	32.7	157.7	76.6
35	-37.1	246.2	29.1	209.1	85.8
25	-6.4	264.1	25.7	257.6	89.1
15	38.4	254.8	24.6	293.2	95.7
5	64.1	251.3	24.8	315.4	104.0
-5	71.3	261.5	23.9	332.8	104.5
-15	70.9	269.9	23.0	340.8	101.8
-25	66.4	261.5	24.6	327.9	107.0
-35	51.0	242.4	29.2	293.5	121.0
-45	26.5	222.2	34.9	248.7	133.3
-55	-11.1	202.0	43.7	190.8	148.1
-65	-59.4	181.3	57.7	121.9	166.3
-75	-72.1	153.6	65.2	81.6	152.8
-85	-77.1	143.9	68.0	66.8	141.9

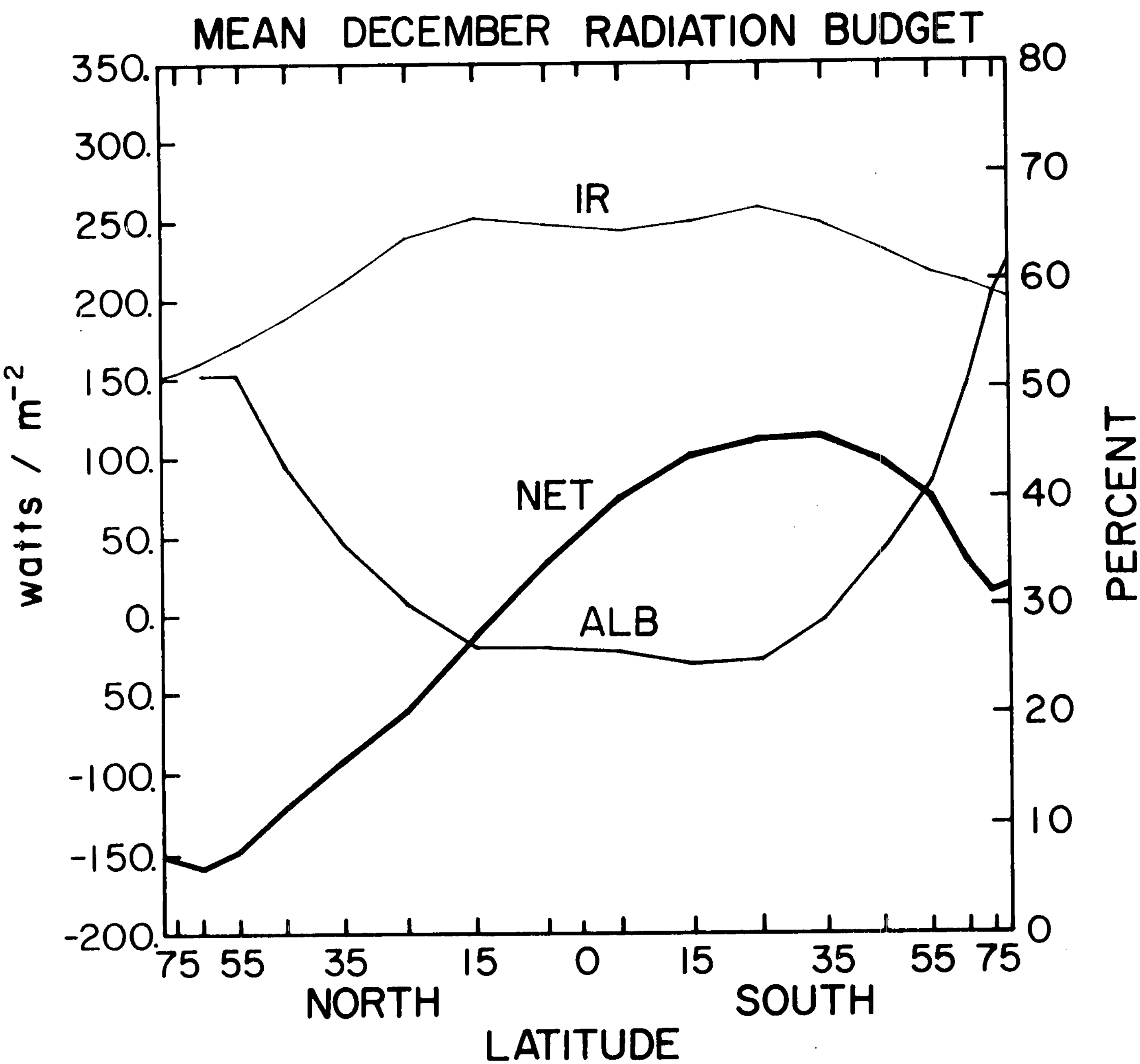

MEAN OCTOBER RADIATION BUDGET
IR
NET
ALB
watts / m⁻²
PERCENT
350.
300.
250.
200.
150.
100.
50.
0.
50.
-100.
-150.
-200.
80
70
60
50
40
30
20
10
0
75 55 35 15 0 15 35 55 75
NORTH
SOUTH
LATITUDE

MEAN NOVEMBER RADIATION BUDGET (WATTS/METER^2)

LAT	NET	IR	ALB	ABS	REF
85	-158.6	158.6	0.0	0.0	0.0
75	-160.7	160.7	0.0	0.0	0.0
65	-158.5	170.8	54.3	12.4	14.7
55	-137.5	185.8	45.8	48.3	40.8
45	-104.9	204.7	37.0	99.8	58.6
35	-76.1	229.8	32.5	153.6	74.0
25	-41.8	250.0	28.7	208.2	83.8
15	4.6	254.5	26.0	259.1	91.0
5	46.4	249.6	25.8	296.1	102.9
-5	73.9	252.8	25.3	326.7	110.6
-15	88.4	260.5	24.8	348.9	115.1
-25	95.3	261.8	25.2	357.2	120.3
-35	95.8	246.2	28.6	342.0	137.0
-45	78.1	229.4	34.4	307.5	161.3
-55	44.5	215.1	42.1	259.6	188.8
-65	-3.6	205.4	52.5	201.7	223.0
-75	-31.0	194.6	61.4	163.6	260.2
-85	-18.0	190.7	60.5	172.7	264.6

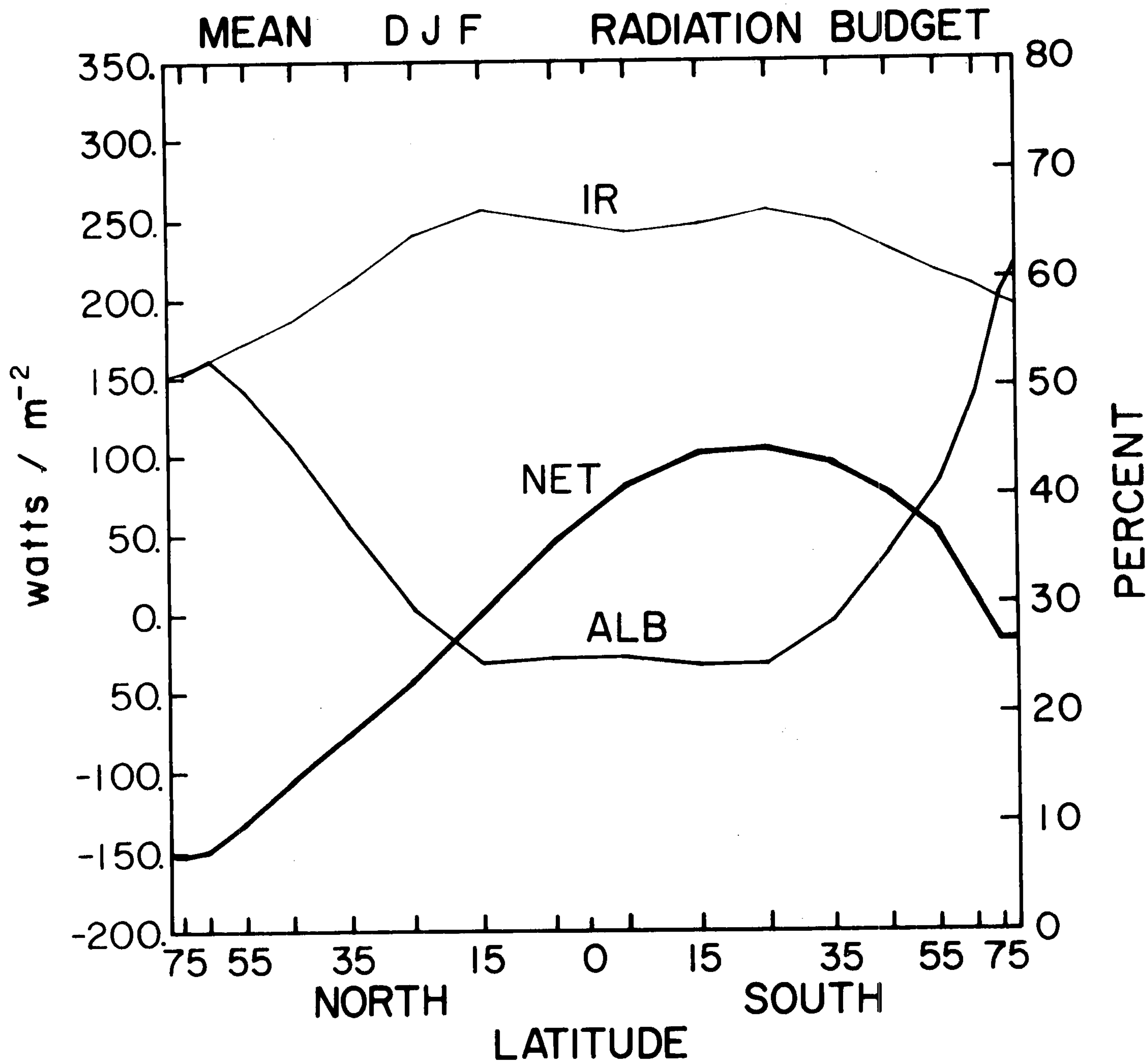
MEAN DECEMBER RADIATION BUDGET (WATTS/METER^2)

LAT	NET	IR	ALB	ABS	REF
85	-152.0	152.0	0.0	0.0	0.0
75	-155.2	155.2	0.0	0.0	0.0
65	-160.4	162.5	51.4	2.1	2.2
55	-149.5	176.8	51.4	27.3	28.9
45	-121.8	192.5	42.8	70.6	52.9
35	-91.1	216.2	35.6	125.1	69.1
25	-59.9	244.4	30.1	184.5	79.4
15	-13.0	256.6	25.9	243.6	85.2
5	33.9	252.1	25.9	286.0	100.0
-5	74.6	248.3	25.6	322.8	111.1
-15	101.7	254.2	24.4	355.8	114.9
-25	112.0	261.8	24.6	373.9	122.0
-35	113.7	251.0	28.4	364.8	144.7
-45	99.6	235.4	34.5	335.0	176.4
-55	77.2	221.1	41.0	298.3	207.3
-65	34.8	214.1	50.4	248.8	252.9
-75	9.2	207.1	59.2	216.3	313.9
-85	12.1	203.3	60.6	215.4	331.3


MEAN DECEMBER RADIATION BUDGET
350.
300.
250.
200.
150.
100.
50.
0.
50.
-100.
-150.
-200.
watts / m^-2
80
70
60
50
40
30
20
10
0
PERCENT
IR
NET
ALB
75 55 35 15 0 15 35 55 75
NORTH
SOUTH
LATITUDE

MEAN D J F RADIATION BUDGET (WATTS/METER^2)

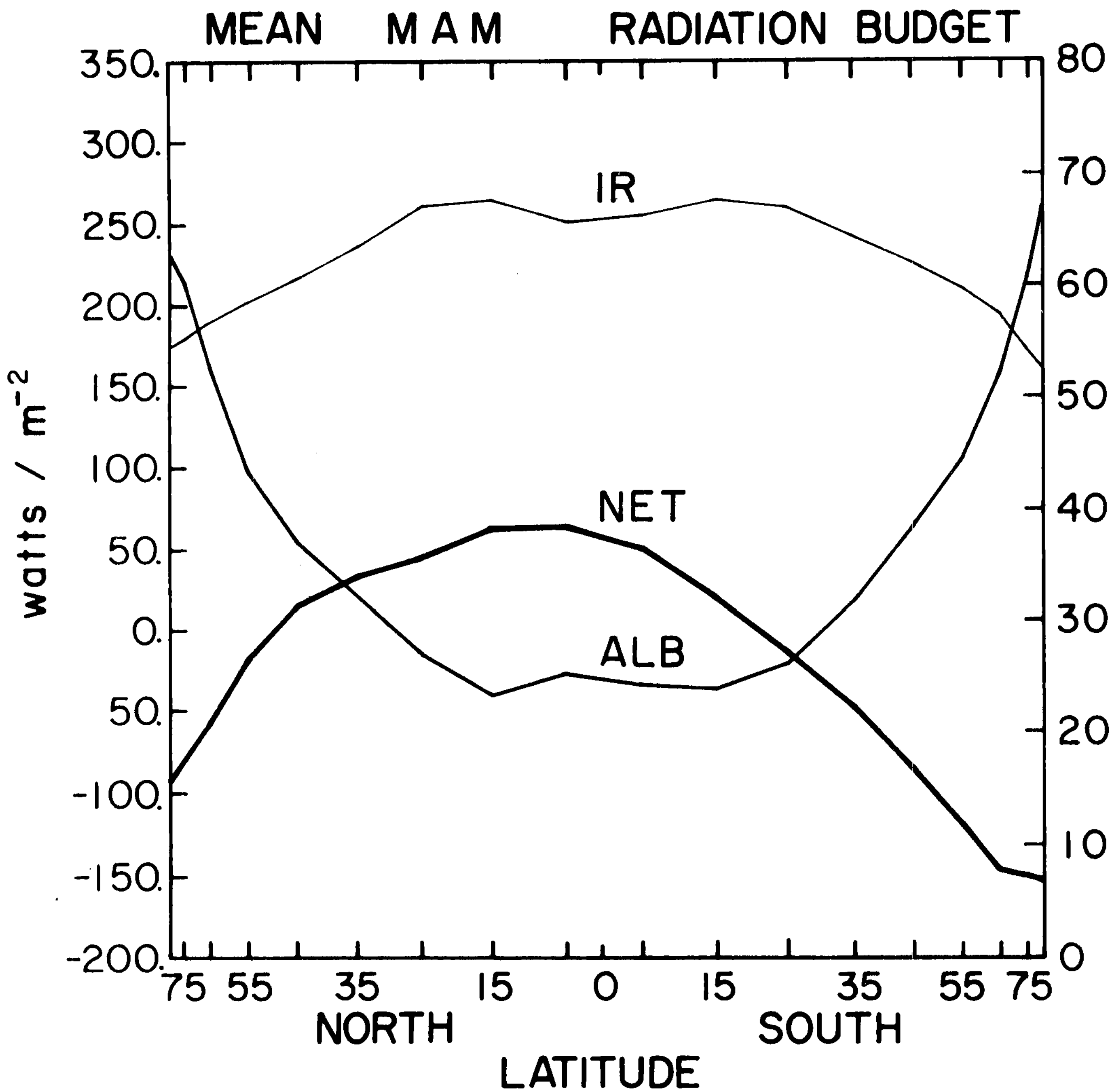
LAT	NET	IR	ALB	ABS	REF
85	-151.1	151.1	0.0	0.0	0.0
75	-152.6	154.0	51.3	1.4	1.5
65	-149.4	162.0	52.6	12.6	14.0
55	-132.3	175.3	49.8	43.0	42.7
45	-104.9	190.4	44.5	85.5	68.5
35	-74.2	215.1	36.9	140.9	82.4
25	-41.6	240.0	29.3	204.4	84.7
15	1.6	261.6	24.4	263.2	85.0
5	45.7	254.0	24.8	299.7	98.8
-5	81.6	247.1	25.0	328.7	109.6
-15	102.0	251.4	24.3	353.4	113.4
-25	104.7	260.3	24.4	365.0	117.8
-35	96.4	253.2	28.1	349.6	136.6
-45	76.8	236.6	34.5	313.4	165.1
-55	51.5	221.4	40.8	272.9	188.1
-65	11.8	212.1	49.3	223.9	217.7
-75	-17.2	200.3	58.9	183.1	262.4
-85	-17.3	196.3	60.8	179.0	277.6



MEAN D J F RADIATION BUDGET
IR
NET
ALB
350.
300.
250.
200.
150.
100.
50.
0.
50.
-100.
-150.
-200.
watts / m^{-2}
80
70
60
50
40
30
20
10
0
PERCENT
75 55 35 15 0 15 35 55 75
NORTH
SOUTH
LATITUDE

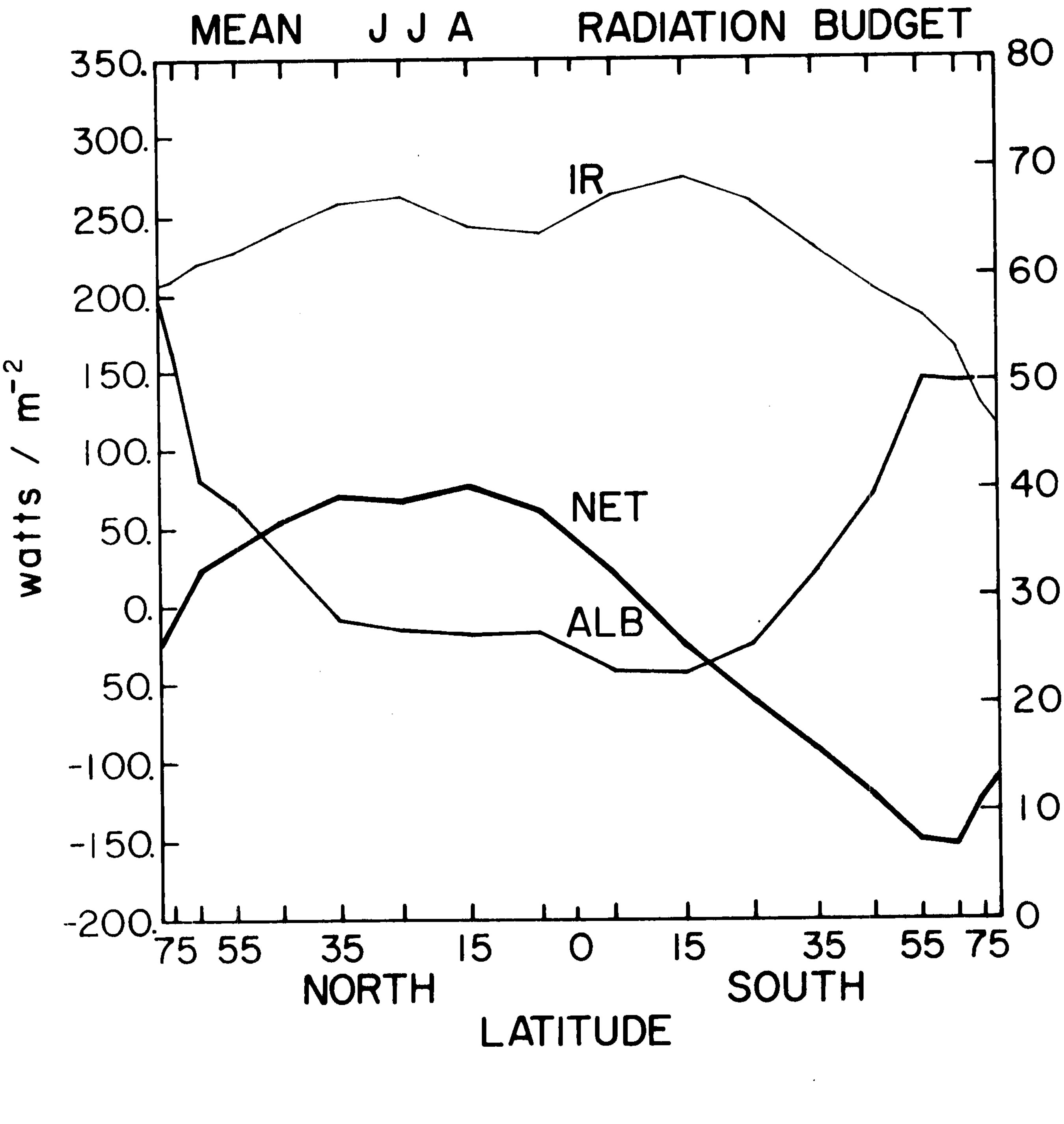
MEAN M A M RADIATION BUDGET (WATTS/METER^2)

LAT	NET	IR	ALB	ABS	REF
85	-90.6	176.7	61.9	86.2	140.0
75	-79.4	181.0	59.4	101.6	148.7
65	-54.2	192.8	52.2	138.7	151.4
55	-13.1	205.0	42.8	192.0	143.6
45	18.0	219.9	36.6	237.9	137.4
35	36.3	240.1	31.9	276.4	129.5
25	47.7	264.8	26.5	312.5	112.7
15	65.1	268.3	22.9	333.4	99.0
5	65.7	254.6	25.0	320.3	106.8
-5	52.5	259.2	23.9	311.8	97.9
-15	22.1	268.4	23.6	290.4	89.7
-25	-12.0	264.3	25.8	252.2	87.7
-35	-47.7	247.3	31.3	199.6	90.0
-45	-85.3	299.8	38.1	144.5	88.9
-55	-118.8	214.0	44.3	95.2	75.7
-65	-147.2	198.3	52.5	51.1	56.4
-75	-150.6	172.5	60.7	21.9	33.8
-85	-153.2	162.0	66.0	8.7	16.9


MEAN MAM RADIATION BUDGET
350.
300.
250.
200.
150.
100.
50.
0.
50.
-100.
-150.
-200.
watts / m^-2
80
70
60
50
40
30
20
10
0
PERCENT
IR
NET
ALB
75 55 35 15 0 15 35 55 75
NORTH
SOUTH
LATITUDE

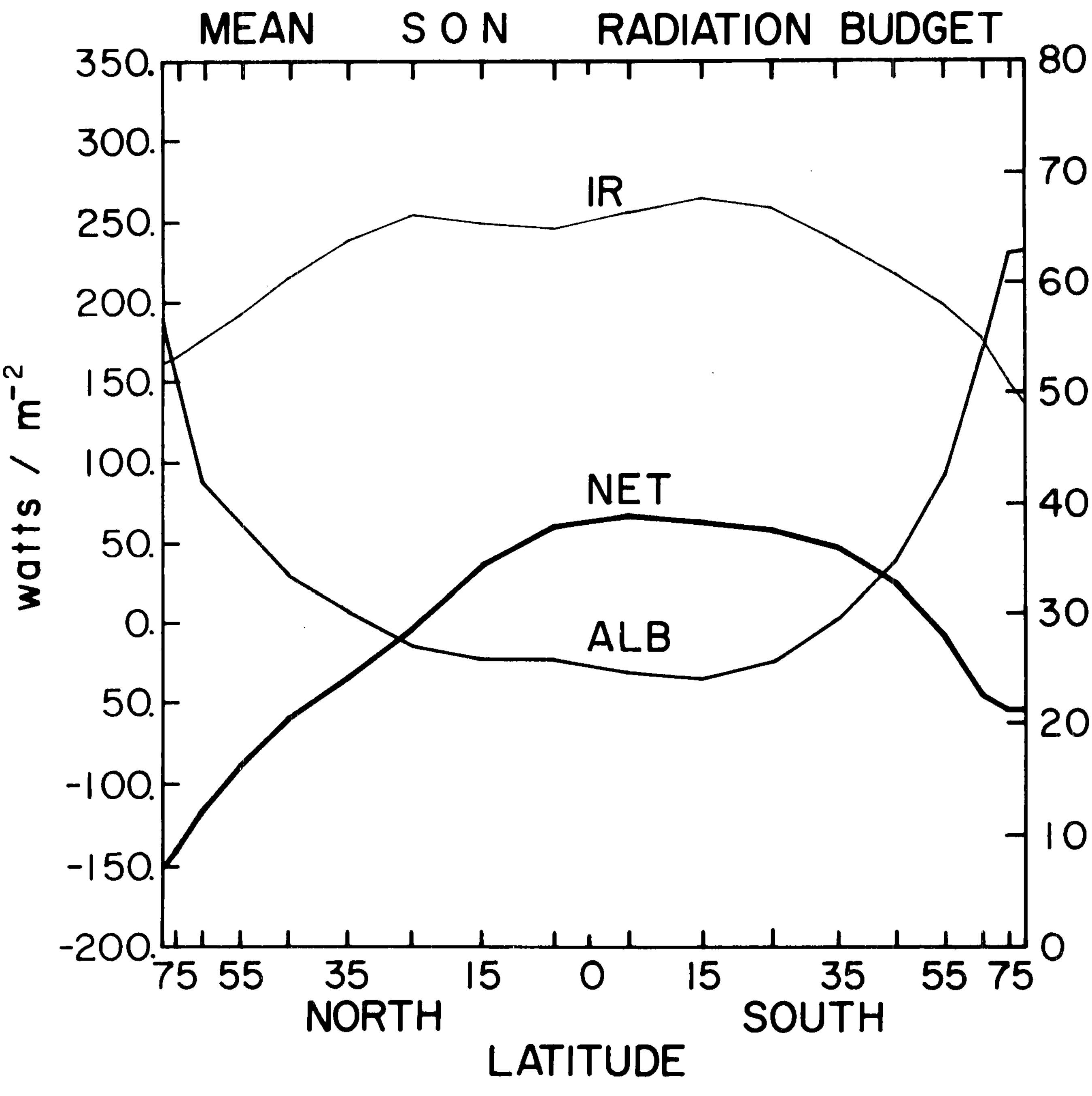
MEAN J J A RADIATION BUDGET (WATTS/METER^2)

LAT	NET	IR	ALB	ABS	REF
85	-21.9	207.0	57.2	185.1	247.4
75	-4.8	209.4	51.5	204.6	217.2
64	26.2	221.2	40.8	247.4	170.5
55	40.6	228.0	38.3	268.6	166.7
45	56.5	244.1	33.4	300.6	150.7
35	71.3	261.1	27.6	332.4	126.7
25	68.1	265.6	26.7	333.7	121.5
15	77.1	246.9	26.4	324.0	116.2
5	60.6	243.0	26.5	303.6	109.5
-5	21.9	267.1	23.0	289.0	86.3
-15	-24.6	278.3	22.6	253.8	74.1
-25	-60.8	263.7	25.3	202.9	68.7
-35	-92.1	234.9	31.9	142.8	66.9
-45	-122.2	210.1	39.3	87.9	56.9
-55	-151.2	191.0	50.2	39.8	40.1
-65	-155.5	167.6	50.0	12.1	12.1
-75	-129.8	131.0	50.0	1.2	1.2
-85	-119.1	119.1	0.0	0.0	0.0


MEAN J J A RADIATION BUDGET
watts / m^-2
350.
300.
250.
200.
150.
100.
50.
0.
50.
-100.
-150.
-200.
80
70
60
50
40
30
20
10
0
PERCENT
IR
NET
ALB
75 55 35 15 0 15 35 55 75
NORTH
SOUTH
LATITUDE

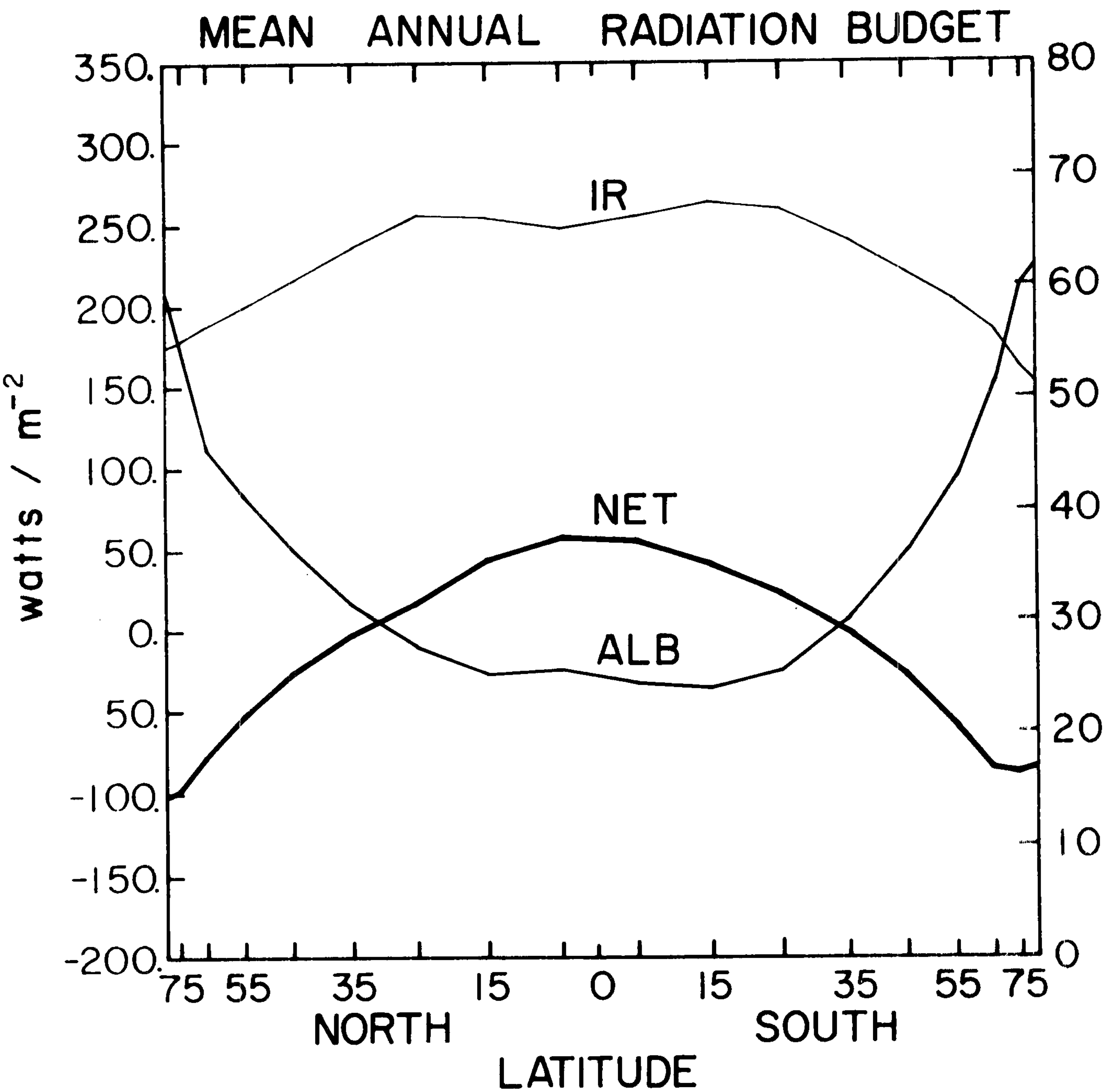
MEAN S O N RADIATION BUDGET (WATTS/METER^2)

LAT	NET	IR	ALB	ABS	REF
85	-151.0	163.8	56.0	12.8	16.3
75	-139.1	168.2	51.5	29.1	30.9
65	-114.6	180.3	41.8	65.7	47.2
55	-86.6	196.2	38.0	109.6	67.2
45	-58.4	219.0	33.0	160.6	79.1
35	-33.9	242.3	29.9	208.4	88.9
25	-3.8	257.6	26.8	253.8	92.9
15	36.3	251.6	25.6	287.9	99.1
5	61.2	248.3	25.5	309.5	106.0
-5	67.9	259.5	24.3	327.4	105.1
-15	64.5	268.8	23.7	333.3	103.5
-25	58.7	262.3	25.1	321.0	107.6
-35	47.3	242.1	29.1	289.4	118.8
-45	24.8	221.2	34.7	246.0	130.7
-55	-8.0	201.3	42.4	193.3	142.3
-65	-47.2	180.3	53.9	133.1	155.6
-75	-57.6	149.5	62.8	91.9	155.1
-85	-57.6	139.9	62.9	82.3	139.5


MEAN SON RADIATION BUDGET
350.
300.
250.
200.
150.
100.
50.
0.
50.
-100.
-150.
-200.
80
70
60
50
40
30
20
10
0
watts / m^{-2}
PERCENT
IR
NET
ALB
75 55 35 15 0 15 35 55 75
NORTH
SOUTH
LATITUDE

MEAN ANNUAL RADIATION BUDGET (WATTS/METER^2)

LAT	NET	IR	ALB	ABS	REF
85	-103.2	174.7	58.9	71.5	102.4
75	-93.6	178.2	54.4	84.6	100.9
65	-72.1	189.1	45.2	117.0	96.5
55	-46.7	201.2	40.7	154.5	106.0
45	-20.9	218.3	35.7	197.4	109.6
35	.7	239.6	30.9	240.3	107.4
25	18.2	258.5	27.2	276.7	103.4
15	45.5	257.1	24.8	302.6	99.8
5	58.9	250.0	25.4	308.9	105.2
-5	56.1	258.2	24.1	314.3	99.8
-15	40.7	266.7	23.6	307.4	95.0
-25	22.0	262.7	25.1	284.7	95.4
-35	.4	244.4	29.6	244.8	102.9
-45	-27.3	224.4	35.8	197.1	109.9
-55	-57.4	206.9	42.6	149.5	111.0
-65	-85.6	189.6	51.3	104.0	109.6
-75	-89.5	163.3	60.2	73.8	111.7
-85	-87.7	154.3	61.7	66.6	107.3


MEAN ANNUAL RADIATION BUDGET
IR
NET
ALB
watts / m^{-2}
PERCENT
350.
300.
250.
200.
150.
100.
50.
0.
50.
-100.
-150.
-200.
80
70
60
50
40
30
20
10
0
75 55 35 15 0 15 35 55 75
NORTH
SOUTH
LATITUDE

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APPENDIX A

Radiant Flux, E_s, at satellite height from the Earth is:

$$E_s = \int_o^{2\pi} \int_o^{\theta_m} L(\theta,\phi)\cos\theta \sin\theta \, d\theta \, d\phi \qquad (A1)$$

where ϕ and θ_m define the right circular cone tangent to the earth and subtended by the earth at the satellite and $L(\theta,\phi)$ is radiance.

If the target is assumed to be homogeneous and isotropic, $\overline{L} = L(\theta,\phi)$, then A1 can be integrated to yield:

$$E_s = 2\pi \, \overline{L} \sin^2 \theta_m \qquad (A2)$$

The interior great circle arc subtended at the earth by this cone is:

$$\alpha'_m = 2\alpha m = 2(\pi/2 - \theta_m) \qquad (A3)$$

From the geometry in figure A1 it is seen that:

$$\theta_m = \sin^{-1}\left(\frac{R}{R+h}\right) \qquad (A4)$$

where h is the height of the satellite above Earth's surface and R is the radius of earth.

Half power area of the earth, as seen by a flat plate sensor on board an earth orbiting satellite at height h is, be equating A2:

$$\tfrac{1}{2}\left(2\pi \, \overline{L} \sin^2 \theta_m\right) = 2\pi \, \overline{L} \sin^2 \theta_H$$

solving for θ_H gives the half angle of this new cone

$$\theta_H = \sin^{-1}\left(\frac{1}{\sqrt{2}} \sin \theta_m\right) \qquad (A5)$$

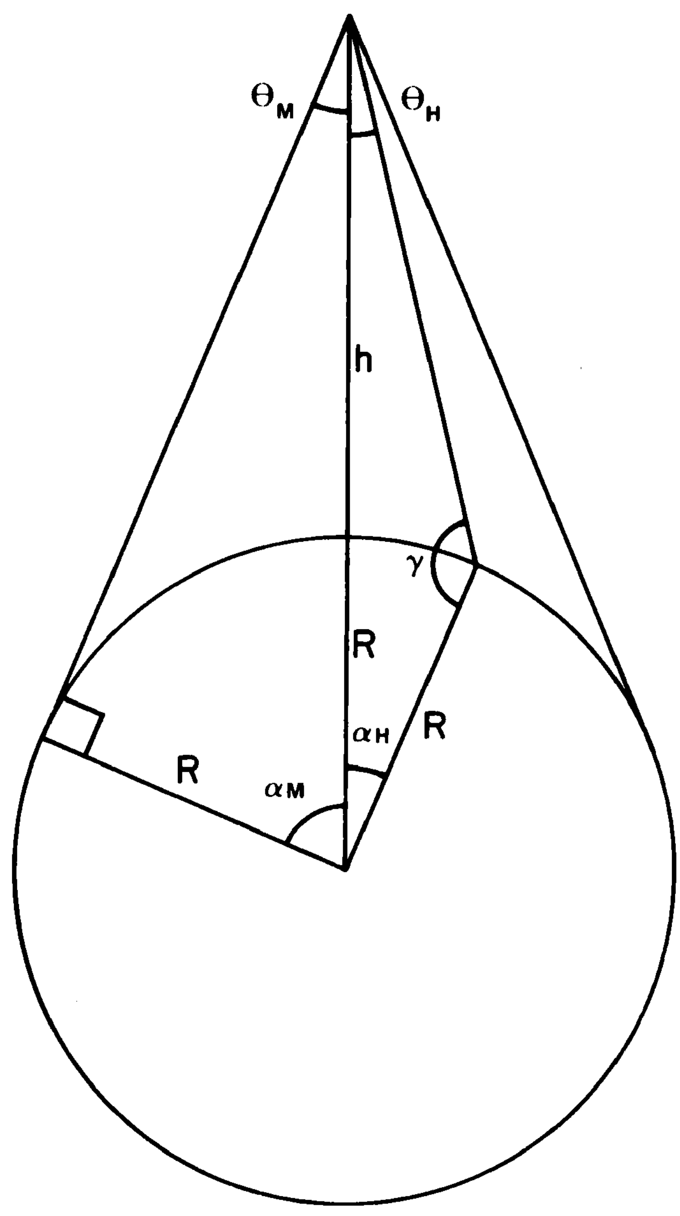

Figure A1

From simple geometry, the half power great circle arc at the Earth's surface is seen to be:

$$\alpha'_H = 2\alpha_H = 2\left[\pi - (\gamma+\theta_H)\right] \tag{A6}$$

where γ from the "law of sines" is

$$\gamma = \sin^{-1}\left(\frac{R+h}{R}\sin\theta_H\right)$$

and the great circle arc distance is $\alpha'_H R$.

The flux at satellite height (hs) can be adjusted to some other reference height (ho). The reference height may be the Earth's surface (ho = 0) or some height representative of the top of the Earth's atmosphere (ho=60km). This adjustment is strictly a geometrical adjustment to the flux with no allowance made for the inhomogeneous and anisotropic nature of $L(\phi,\theta)$ over the target as seen at satellite height.

The geometrical multiplier, β, using A2 is:

$$\beta = \frac{E_s}{E_o} = \frac{\sin^2\theta_m}{\sin^2\theta_m} = \left(\frac{R+hs}{R+ho}\right)^2 \tag{A7}$$

so that flux at the new reference level is:

$$E_o = \beta E_s$$

Table A1 gives various values of the factors for each of the satellites with flat plate sensors.

APPENDIX B

The equation for net radiation is:

$$N = (1 - A)\ S - I \tag{B1}$$

where each term is

A, albedo

S, solar flux at the top of the Earth's atmosphere

I, infrared exitance or thermal radiation.

The total uncertainty in the net can be expressed by applying a Taylor series expansion to small departures from the true value:

$$\sigma_N^2 = \sigma_S^2\left(\frac{\partial N}{\partial S}\right)^2 + \sigma_A^2\left(\frac{\partial N}{\partial A}\right)^2 + \sigma_I^2\left(\frac{\partial N}{\partial I}\right)^2 \pm 2\left[\sigma_{SA}{}^2\left(\frac{\partial N}{\partial S}\right)\left(\frac{\partial N}{\partial A}\right) + \sigma_{SI}{}^2\left(\frac{\partial N}{\partial S}\right)\left(\frac{\partial N}{\partial I}\right) + \sigma_{AI}{}^2\left(\frac{\partial N}{\partial A}\right)\left(\frac{\partial N}{\partial I}\right)\right]$$

The first three terms on the right-hand side treat the uncertainty of each component independently. The covariance or correlated uncertainties are in brackets. It is known that uncertainty in the solar constant is, to some extent, negatively correlated with uncertainty in albedo since albedo is not measured directly, but is computed as function of solar insolation. Thus, the first term in brackets is negative. The second term in brackets can be eliminated since uncertainties in solar constant and infrared exitance are independent. The third term in brackets tends to be negative since uncertainties due to sensor degradation in a combined system of black and white sensors are negatively correlated. However, not all of the data in this report were taken from such a combined system.

The effect of the two negative terms is to reduce total uncertainty in the net. If we consider a worse case when all uncertainties are independent we can simplify B2 to an expression commonly referred to as, "the law of propagation of independent errors."

$$\sigma_{iN} = \left[\sigma_S^2 \left(\frac{\partial N}{\partial S}\right)^2 + \sigma_A^2 \left(\frac{\partial N}{\partial A}\right)^2 + \sigma_I^2 \left(\frac{\partial N}{\partial I}\right)^2 \right]^{\frac{1}{2}} \qquad \text{(B3)}$$

This expression has been applied to each monthly set of data. In another form (B3) can be applied to obtain uncertainty in monthly means if each monthly set, or each satellite measurement, has an uncertainty independent of measurements from other satellites so that

$$\bar{\sigma}_N^n = \left[\sum_{i=1}^{n} \left(\frac{\sigma_{in}}{n}\right)^2 \right]^{\frac{1}{2}} \qquad \text{(B4)}$$

where n is the number of monthly data sets in each mean month.

Uncertainty in the seasonal mean must consider that uncertainty in each of three mean months of a season are not independent since measurements from the same satellite frequently appear in each mean month. Therefore, an equation in the form of B2 must consider all six terms with positively correlated uncertainties. Such an equation can be simplified to be:

$$\bar{\sigma}_N^k = \left[\frac{1}{K} \sum_{i=1}^{k} \left(\bar{\sigma}_N^n\right)_i^2 \right]^{\frac{1}{2}} \qquad \text{(B5)}$$

where K is the number of mean months in a mean season ($k \leq 3$).

An equation identical to B5 can be applied to each mean season uncertainty to obtain uncertainty in the annual mean net radiation.