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Aircraft measurements of the albedo of the earth's surface and of clouds over India

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ABSTRACT. Measurements of global and reflected solar radiation and of the earth's albedo over extensive land areas in India and over the adjoining seas were made from a Canberra aircraft during July-August 1972 as part of an Indo-U.K. Project Exercise Storm Exchange. Two thermoelectric pyranometers, one facing upwards and the other facing downwards, were used to measure the global and reflected solar radiation, a photographic recorder with suspended coil mirror galvanometers recording the data continuously in flight.

Twenty aircraft flights were made from three bases, 7 from Bangalore, 8 from Poona and 5 from Calcutta, over both land and sea, covering areas from 7°N to 24°N and 71°E to 89°E. The aircraft flew at heights above ground/sea from 150 to 15,000 m.

The values of global solar radiation recorded were of the order of 1·60 to 1·80 cal/cm²/min at heights of 4,600 m to 15,000 m, when there were no clouds; thin cirrus reduced this value by about 16 to 20 per cent and other clouds by larger amounts depending on their type and thickness.

The albedo over the sea was found to vary between 0·04 to 0·13, depending on the state of the sea and the solar elevation and that over the ground between 0·10 to 0·25. The albedo over active cumulus clouds was about 0·40 to 0·60 and that over cumulus of smaller extent between 0·25 and 0·40. Stratocumulus clouds have smaller albedo, 0·20-0·40 and stratus, 0·15-0·25. The albedo of altostratus clouds was found to lie between 0·25 and 0·35. The albedo of the cirrus remains of dissipating cumulonimbus clouds was about 0·45 to 0·55. In the growing cumulus cloud the albedo changes from 0·20 to 0·55 depending on the stage of growth. Albedo values change from 0·16-0·27 to 0·30-0·36, when stratus and stratocumulus clouds are associated with cirriform clouds.

The observations are compared with satellite and ground observations of surface albedo over India.

1. Introduction

Albedo is defined as the ratio of reflected to incident radiation integrated over the solar spectrum from 0·2 to 4 μm. Considerable data on the albedo of the earth's surface and of clouds obtained from aircraft over various parts of the world have been published, although direct measurements over the tropics especially over the tropical oceans remain sparse. Extensive aircraft measurements of the albedo over the tropical Atlantic were made during the Barbados Oceanographic and Meteorological Experiment (BOMEX) and are planned during the GARP Atlantic Tropical Experiment (GATE) in 1974. The most extensive aircraft albedo measurements over a continental area were made over a five year period by Gayevsky (Barashkova *et al.* 1961) over the USSR. Recent measurements from meteorological satellites of planetary albedo by scientists of the NASA Goddard Space Flight Center, the University of Wisconsin and the Main Geophysical Observatory and the University of Leningrad have provided extensive information on planetary albedo on a global scale. The mean annual earth's planetary albedo, which was earlier accepted to have a value of 0·35, is now given as 0·29; or our planet is somewhat darker than previously estimated and warmer. The tropical regions are especially noted to have a lower albedo than believed in pre-satellite days.

The present paper reports and discusses some of the results of the first extensive aircraft measurements made over India and the adjoining seas during 1972 and 1973 and their effect on radiation budget studies.

2. Aircraft measurements

2.1. *Canberra flights*

2.1.1. *Organisation* — During the summer monsoon months July-September 1972, the India Meteorological Department took part in a joint Indo-U.K. research project, Excercise Storm Exchange for the study of atmospheric turbulence at high levels over India. The project involved the use of a specially instrumented Canberra research aircraft loaned by the Royal Aircraft Establishment, Farnborough, U.K. for three months. Research groups in India formulated and carried out extensive flight programmes over India for collecting data on several atmospheric aspects, mainly on turbulence in clear air and around clouds, and turbulence associated with southwest monsoon, mountain waves, easterly jet streams etc. The Excercise as a whole involved a total of 167 hours of flying over 120,000 km covering various regions in the south and northeast of India from 7°N to 24°N and 71°E to 89°E. Of these 40 hours flight was at heights of 100-400 m and the rest from 4000-15000 m. The aircraft was flown and maintained by the Indian Air Force throughout the three month's duration of the experiment.

This unique opportunity was availed of to carry out aircraft measurements of the albedo of the earth's surface and of clouds over India during the period July to September 1972. Although surface measurements of the reflected solar radiation and the albedo of the earth's surface had been made at the ground at a few stations in India since 1963, no measurements over extended areas had been made. The measurements have since been continued from a Dakota DC-3 aircraft used in cloud seeding experiments.

The RAE Canberra WH 793 used in the Excercise Storm Exchange was a prototype developed from the PR7, by increasing the wind area, fitting more powerful engines and power-controlled ailerons and rudder. One of the wing tip tanks carried a weather radar and the other a foreward looking camera. The aircraft was also equipped with a pitot tube to measure both static and dynamic pressures, incidence vanes for detecting the flow direction, accelerometers for indicating normal and lateral accelerations, a total temperature probe, pitch angle and pitch rate indicators, bank angle and elevation angle indicators and pressure altitude and air speed indicators. Navigational aids include air direction finders, visual omnirange system, TACAN and the Doppler navigational systems.

The signals produced by the instruments were recorded on two oscillograph recorders, one running slow and the other fast. Signals received by these recorders were traced on photographic films which were developed after the completion of each flight. The slow recorder was kept recording throughout the flight while the fast recorder was activated only when relatively

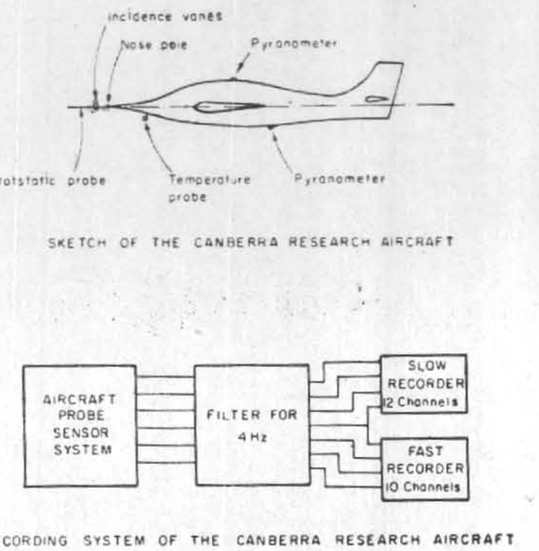

Fig. 1. Instruments and data acquisition system of RAE Canberra WH 793 Research Aircraft

fast changes were observed in the flight environment. The parameters recorded on the slow recorder were air speed, barometric height, normal acceleration, outside air temperature, elevator angle and pitch attitude and global and reflected solar radiation.

The aircraft had a ceiling of 15500 m and flew at levels above land/sea varying from 150 to 15000 m. Fig. 1 shows the instruments and data acquisition system of the RAE Canberra WH793 research aircraft.

The complete excercise was executed from four major bases of operation, Bangalore, Poona, Calcutta and Agra (Fig. 2). About eightysix sorties were made from the different bases. Radiation measurements were made during seven flights carried out from Bangalore (12° 57′N, 77° 38′E) during July 1972, eight flights from Poona (18° 35′ N, 77°55′E) during July-August 1972, and five sorties from Calcutta (22°39′N, 88°27′E) during August 1972.

The types and amounts of cloud were noted by the aircraft navigator with the time of observation and the altitude of the base and top of the cloud. The direction and distance at which the cloud appeared was estimated if the flight plan did not permit passage through the cloud.

2.1.2. *Instrumentation* — The equipment used was simple. Two thermoelectric pyranometers, developed in the Central Radiation Laboratory at Poona and constructed in the Departmental workshops were used as sensors to measure the incoming solar radiation from the sun and the

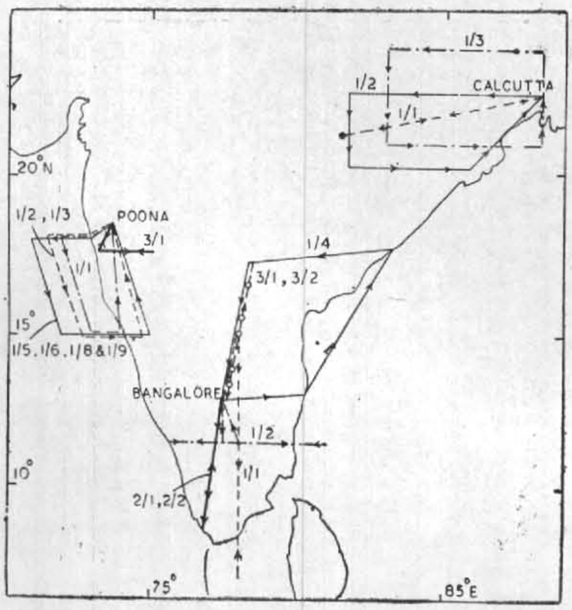

Fig. 2. Flight path of Canberra Aircraft

entire sky and the outgoing solar radiation reflected or scattered backwards. The sensing surface was protected by two concentric hemispherical optical glass domes mounted on threaded brass rings. A desiccator with silica gel kept the interior of the pyranometer dry. The pyranometers were found to be rugged and capable of withstanding severe mechanical vibration and shock. The hemispherical glass domes were also found to be stable if fixed firmly on their rings with epoxy cement.

Miniature mirror galvanometers of the suspended coil type (manufactured by Societe de Fabrication d'Instruments de Mesure, France) with suitable resistors in series recording on photographic paper were used for obtaining continuous records of the outputs of the pyranometers. Due to lack of space, the more sensitive potentiometric recorder could not be installed

2.1.3. *Installation of instruments* — The two thermoelectric pyranometers were mounted on the top and bottom surfaces of the aircraft fuselage, with their massive brass mounts let into the aircraft body so that only the thermopile with its glass domes projected beyond the fuselage. The aircraft surrounding served as an anti reflective shield for the pyranometers. There was no significant obstruction to a free horizon for both sensors and the thermopile surfaces were adjusted to be horizontal when the aircraft was in its normal cruising altitude in level flight and normal descent. Only radiation data when the aircraft was in horizontal flight or nearly so (bank and pitch angles not exceeding $\pm 3°$ generally) and the outputs from the sensors had stabilized, were taken into consideration to avoid errors due to the pitch and yaw of the aircraft.

The downward facing pyranometer for the measurement of reflected solar radiation had been originally mounted on the wing near the under-carriage but was later shifted to the lower surface of the fuselage, since in the original location violent jerks due to the sudden closing of the undercarriage after take off caused the outer dome of the pyranometer to become loose and later to be blown off. The top sensor became defective as a result of damage to the black painted aluminium foil on 1 September. So, though the flights continued till 21 September 1972, global data are available only to 1 September 1972.

2.1.4. *Radiation data evaluation and presentation* — The outputs of the sensors were continuously recorded on photographic paper in the slow recorder. The individual data had to be evaluated manually and this operation has been time consuming.

Individual measurements of short term averages of global solar radiation even on the ground are subject to errors of the order of ± 5 per cent unless very great care is taken in the operation and maintenance of the instruments. So aircraft measurements of global and reflected solar radiation with unattended instruments have perforce to be subject to considerably larger errors. Further, although the field of view of the pyranometers is 180°, the effective field looking at the clouds is reduced to about 90° on account of the Lambertian cosine effect; and the predominant cloud reflection to the aircraft is therefore contained in this solid angle. No corrections could be and have been applied for the temperature of the pyranometers, which was not known. The temperature drop from the outside air of the order of — 75° C at its lowest to the cabin at — 65°C occurred across the pyranometer. The two sensors are also at different temperatures when the upper one is in sunlight and the lower one in the shadow, but this temperatures difference may be of the order of only 2° to 3°C (Robinson 1959). Shortwave radiation in the form of skylight can fall on the lower sensor if the level of observation is increased to a point that permits the instrument to see above the horizon; direct sunlight at very low sun angles can also fall on the lower sensor vitiating results.

2.1.5 *Calibration* — The two thermoelectric pyranometers were calibrated at Poona against a working standard Ångström pyrheliometer. It was also compared with a reference standard Kipps pyranometer for different angles of elevation of the

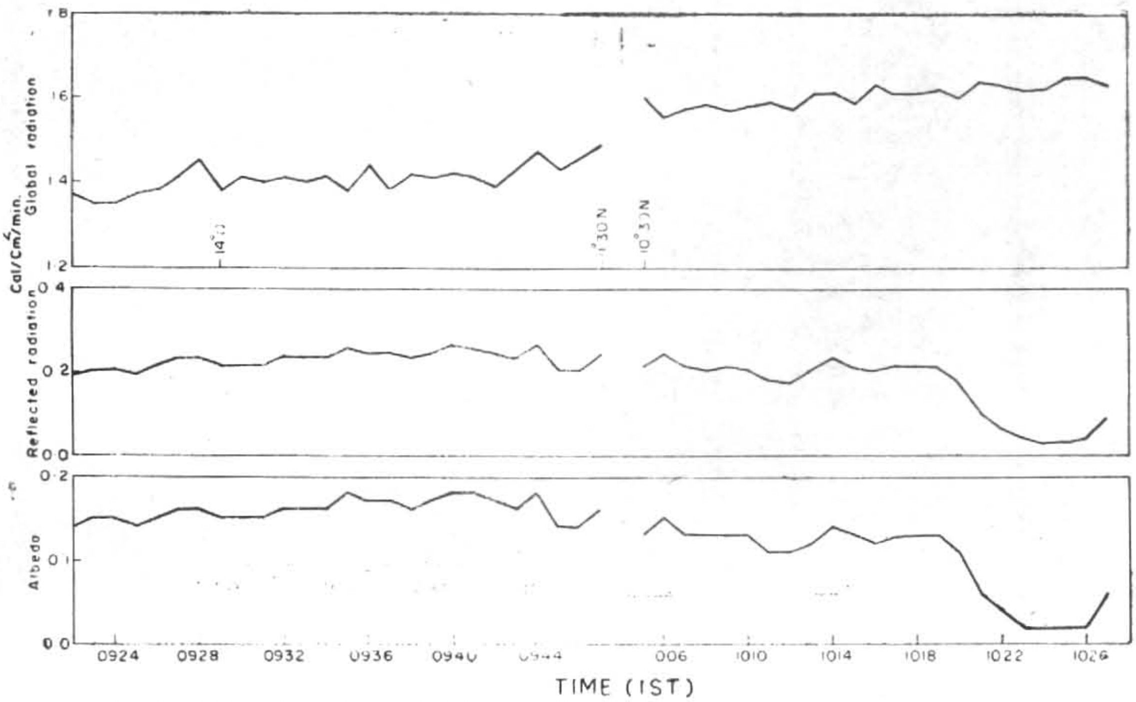

Fig. 3. Values of global and reflected solar radiation and albedo on 18 July 1972 on flight from 15°N-7°N along 77°38'E at a height of 14,300 m

sun over a number of days, after the sensing surfaces had been checked and adjusted in the laboratory for azimuth response. The time constant of the pyranometers is of the order of 30 seconds and their azimuth and cosine response within ± 2 per cent.

A resistance of 70 ohms was connected in series with the SFIM mirror galvanometer in order to obtain a voltage sensitivity of 11.8 mV for a deflection of 86 mm on the photographic record for recording the output of the global pyranometer. The recording millivoltmeter was calibrated on 13 July 1972 with a source of e.m.f. and a potentiometer. The calibration was found to be linear. The resistance of the leads from the global pyranometer to the recording millivoltmeter was 4.7 ohms and a deflection of 24.8 mm on the record would correspond to a radiation flux of 1 cal/cm²/min. The recorder was calibrated again on 31 July 1972 and after completion of the flights on 22 September 1972. The recording millivoltmeter for the reflected solar radiation with a series resistance of 10 ohms had a voltage sensitivity of 7.6 mV for deflection of 86 mm on the record and with a lead resistance of 2.3 ohms from the reflected radiation pyranometer, the scale value of the record for reflected radiation was 53.6 mm per cal/cm²/min.

2.2. *DC-3 Flights*

During the monsoon and post monsoon months of 1973, the Institute of Tropical Meteorology at Poona organized a series of flights using an instrumented Dakota DC-3 aircraft for weather modification studies in the Bombay-Poona region. This opportunity was again availed of to carry out additional aircraft measurements of global and reflected solar radiation and albedo over extended areas around Poona during 1973. The altitude of the aircraft during flight was between 600-1200 m above ground level. The instruments used were similar to those installed on the Canberra aircraft. The recording was done on a Honeywell potentiometric recorder having a full scale deflection of 0-15 mV and a chart speed of 300 cm per hour. An inverter was used to convert the 12 volts D.C. supply available on the aircraft to the 230 volts A.C. required for the recorder. Observations made on two days in October 1973 over a region 50 km to the east of Poona are presented.

3. Results

3.1. The values of the global and reflected solar radiation and the albedo of the earth's surface made during the Canberra aircraft flights over India during July-August 1972 are summarised in Table 1. Table 2 contains similar data for cloud albedo obtained during the flights. Table 3 contains similar data for the DC-3 flights.

3.2. *Individual Canberra flights*

3.2.1. *18 July 1972* — On 18 July 1972 the Canberra aircraft carried out a sortie from latitude 15°N to 7°N along the longitude 77°38'E (Fig. 2).

TABLE 1

Global and reflected solar radiation and albedo of the earth's surface over India and the adjoining seas (Canberra Flights)

Date (1972)	Solar radiation (cal/cm²/min) Global	Reflected	Flight level amsl (m)	Time (IST)	Solar elevation (degrees)	Type of underlying surface	Albedo	Remarks
				Base : Bangalore				
18 Jul	1·60–1·62	0·21–0·18	14330	1005–1020	55–58	Ground	0·11–0·13	No cloud above
	1·62–1·63	0·06–0·09	14330	1022–1027	58–59	Sea	0·02–0·06	Do.
	1.28–1.40	0·10–0.13	6100	1431–1435	57–55	Do.	0.09–0.11	Do.
19 Jul	1·66–1·56	0·10–0·04	15240	1500–1501	50	Do.	0·03–0·06	Do.
				Base : Poona				
29 Jul	1·63–1·65	0·23–0·26	4570	1145–1147	77–78	Ground	0·14–0·16	Do.
1 Aug	0·17–0·27	0·01	150	0759-0803	22–23	Sea	0·13–0·16	*Ac, As* clouds at 4570′
	0·20–0·45	0·03–0·05	150	0806–0843	23–32	Disturbed sea	0·07–0·16	*Ac, As* clouds with *Cu* below
	0·50–0·62	0·03–0·04	150	0848–0902	33–38	Sea	0·07–0·08	Do.
	0·40–0·55	0·03–0·05	150	0858–0902	37–38	Do.	0·07–0·09	Higher cover of *As Ac, Sc*, and *Cu*
	1·10–1·11	0·16–0·21	3200	0926–0928	44	Earth	0·15–0·19	No cloud above
	1·60–1·63	0·18–0·21	4720	1207–1210	80–81	Sea	0·11–0·13	Do.
	1·62–1·72	0·27–0·32	4570	1300–1306	85–83	Ground	0·16–0·19	*Ac* cloud in patches above
	1·42–1·45	0·18–0·22	6100	1512–1514	56	Sea	0·13–0·16	*Ci* clouds above
	1·39–1·45	0·14–0·20	6100	1518–1525	55–53	Do.	0·10–0·14	Do.
5 Aug	1·03–1·18	0·11–0·15	4570	0958–1012	51–52	Do.	0·10–0·12	Gradual increase of global radiation
	1·31–1·34	0·14–0·17	4420	1021–1026	56–57	Do.	0·10–0·13	No cloud above
	1·30–1·38	0·15–0·18	4420	1030–1036	59–61	Do.	0·11–0·13	Do.
	1·47–1·54	0·21–0·28	4270	1052–1100	65–67	Ground	0·14–0·19	*Ci* clouds above
	1·44–1.56	0·18–0·26	4270	1103–1107	67–68	Do.	0·12–0·17	Flight over Western Ghats
	1·67–1·70	0·13–0·17	6100	1430–1435	66–65	Sea	0·08–0·11	No cloud above
8 Aug	1.01–1·12	0·14–0·15	4570	0942–0946	45–46	Do.	0·13–0·14	Do.
	1·06–1·10	0·13–0·14	4570	0950–0954	48–49	Do.	0·12–0·13	Do.
	1·19–1·28	0·12–0.16	4570	1009–1013	53–55	Do.	0·10–0·13	Do.
	0·89–0·94	0·12–0·16	6100	1611–1617	43–41	Do.	0·13–0·16	Do.
				Base : Calcutta				
27 Aug	1·50–1·58	0·27–0·29	4880	1034–1039	66–67	Ground	0·17–0·19	Thin *Ci* cloud above

South from 15°N to 11°30′N it flew at a level of 14,300 m and from 10°30′N to 7°N at 14,000 m. The values of incoming and reflected solar radiation and albedo for the two portions of the flight from 15°N to 7°N and back are given in Fig. 3.

As seen from the navigator's report and as judged from synoptic observations made at stations in the vicinity of the flight path, the aircraft was flying over scattered *Cu*, *St*, *Sc* and *As* clouds totalling about 6 oktas from 15°N to 10°30′N. With a ground speed of 12 km/min, the values of incoming and reflected radiation evaluated every minute correspond to an average value over 12 km, allowing for the time constant of the pyranometers. As seen from Fig. 3 the albedo of the clouds and of the ground seen through portions not covered by clouds, varied from 0.13 to 0.16. The intensity of the incoming solar radiation ranged from

TABLE 2

Typical values for clouds over India — Canberra flight

Date (1972)	Solar radiation (cal/cm²/min) Global	Reflected	Flight level amsl (m)	Time (IST)	Solar elevation (degrees)	Cloud Amt. (Octa) Type	Albedo	Remarks
				Base : **Bangalore**				
18 Jul	1·28–1·36	0·16–0·40	6100	1423–1431	61–58	4 *Cu*	0·16–0·29	
	1·18–1.34	0·16–0·29	12200	1530–1542	47–40	4 *Cu*	0·14–0·22	
	0·98–0·65	0·24–0·46	15240	1652–1724	27–14	4 *Cu*	0·32–0·62	Low solar elevation
25 Jul	0·72–0·99	0·09–0·15	6250	0903–0924	41–45	3 *St*	0·10–0·17	
	0·88–1·01	0·19–0·30	6160	0925–0938	45–47	3 *St* 3 *Cu*	0·21–0·34	*Cu* cloud above *St*
	1·28–1·36	0·25–0·40	14330	1606–1615	38–36	3 *Sc* 2 *Ac*	0·19–0·22	
	1·24–1·32	0·27–0·46	14330	1619–1625	35–33	3 *Sc* 2 *Ac* 4 *Cs*	0·21–0·37	*Cs* spread over *Sc* and *Ac*
				Base : **Poona**				
1 Aug	1·63–1·66	0·23–0·46	4720	1131–1136	72–73	1 *Sc* 3 *Cu*	0·30–0·46	*Cu* in different stages of growth
	1·38–1·40	0·20–0·24	6100	1525–1527	53	3 *St*	0·16–0·17	
	1·38–1·40	0·24–0·44	6100	1527–1529	53–52	4 *St* 4 *As*	0·24–0·32	*As* cover over *St*
5 Aug	1·59–1·62	0·26–0·44	6100	1402–1406	71	3 *Sc, Cu*	0·16–0·22	Albedo mainly due to *Sc*
	1·60–1·61	0·44–0·54	6100	1402–1406	71	3 *Sc, Cu*	0·27–0·34	Albedo mainly due to *Cu*
	1·58–1·59	0·21–0·40	6100	1411–1418	70–69	2 *Sc* 2 *Cu* 4 *As*	0·16–0·25	Albedo mainly due to *Sc*
	1·58–1·59	0·57–0·61	6100	1411–1418	70–69	Do.	0·31–0·39	*As* above *Sc, Cu*
	1·65–1·69	0·17–0·38	6100	1435–1445	65–62	2 *St* 3 *Sc*	0·12–0·17	Albedo mainly due to *St*
	1·26–1·28	0·19–0·27	6100	1508–1512	55–53	6 *St* 2 *Sc*	0·15–0·21	
	0·93–1·18	0·25–0·35	6100	1523–1526	50–49	8 *Sc, Cu* 2 *Ac*	0·26–0·30	
	1·01–1·16	0·24–0·32	6100	1527–1528	49	8 *Sc, Cu*	0·23–0·26	
8 Aug	1·11–1·35	0·21–0·33	6100	1528–1538	62–58	2 *Cu*	0·16–0·19	
	1·14–1·24	0·24–0·34	6100	1538–1546	58–55	2 *Cu* 3 *As*	0·22–0·29	
				Base : **Calcutta**				
23 Aug	1·38–1·41	0·41–0·60	5490	1002–1008	62	5 *Cu*	0·30–0·43	*Cu* of varying thickness
	0·14–0·62	0·09–0·32	4880	1552–1554	35	4 *Sc* 4 *As*	0·50–0·80	*As* just below aircraft
	0·58–0·90	0·14–0·30	4880	1555–1606	35–32	6 *Sc* 6 *Ac*	0·16–0·38	
	0·19–0·46	0·07–0·25	4720	1625–1635	27–23	5 *Sc, Cu*	0·38–0·80	*Cu* of varying thickness
25 Aug	1·96–1·99	0·62–0·92	15240	1157–1203	77	Dissipating *Cb*	0·31–0·46	*Cb* 11580 m thick, aircraft 915 m above *Ci* top
	1·80	0·50	14630	1208–1214	76	Do.	0·28	Aircraft about 300 m above *Ci* top of *Cb*

1.37 cal/cm^2/min to 1.49 cal/cm^2/min. The average value of reflected solar radiation during this period was 0.22 cal/cm^2/min. The cloud amounts were smaller for the flight southwards from 10°30′N. The increase with time in the incoming solar radiation is mainly due to the increase in solar elevation. The variation in reflected solar radiation was small till 1019 IST ranging between 0.24 and 0.17 cal/cm^2/min when, as the aircraft crossed coast, at the tip of the Indian Peninsula, both reflected solar radiation and albedo showed a sharp fall. The minimum value of albedo recorded over sea was 0.04.

3.2.2. *25 July 1972* — The values of global and reflected solar radiation and albedo during a flight carried out on 25 July 1972 between Bangalore (13°N) and Trivandrum (8°N) are given in Table 1. During this flight the aircraft was over cirrostratus clouds in patches, with varying amounts of *Cu*, *Sc* and *As* clouds below. As judged from cloud observations made at stations around the flight path, the amount of *Cu*, *Sc* and *As* clouds varied between 3 to 8 oktas, with a marked decrease of clouding around latitude 11°N. In the first half of the flight from Trivandrum to Bangalore, while there was only a gradual decrease in the incoming global solar radiation, there were appreciable fluctuations in the reflected solar radiation and the albedo. The variations of reflected solar radiation ranged between 0.18 and 0.54 cal/cm^2/min and albedo between 0·15 and 0·38. The marked fall in albedo around latitude 11°N is a result of a decrease in clouding. The maximum value of albedo of 0.38 recorded over *Cu*, *Sc* and *As* is rather low due to the high altitude of the aircraft. On the return flight from Bangalore to Trivandrum immediately following, the values of reflected solar radiation and albedo varied between almost the same limits. The decrease in the global solar radiation is due to decreasing angles of elevation of the sun.

3.2.3. *26 July 1972* — The Canberra made flights from Bangalore (13°N) to Hyderabad (17° 30′N) and back. The flight level was 12,200 m during the flight from Bangalore to Hyderabad and between 13,000 to 14,000 m on the return flight. The sky above was clear. North from Bangalore upto 16°N the clouds below the aircraft consisted of *Ci*, *As* and *ScCu* 3, 5 and 6 oktas respectively. The top of *Ci* was at 10,000 m, *i.e.*, about 2,000 m below the aircraft. Beyond 16°N upto Hyderabad the clouds below changed to 2 oktas of *Sc*, *Cu* and 4 oktas of *Ac*. During the flight from Bangalore to Hyderabad the global solar radiation varied between 1.69 to 1.48 cal/cm^2/min and the reflected solar radiation between 0.28 to 0.56 cal/cm^2/min. The albedo ranged between 0.16 to 0.33. The albedo is mainly that of *As*, *Sc* and *Cu* modified by the presence of *Ci*. The low value of albedo is as observed earlier, due to the altitude of the aircraft above the cloud, causing attention of the reflected radiation reaching the aircraft. The pattern of the values of global and reflected solar radiation and of albedo is similar during the return flight of the aircraft from Hyderabad to Bangalore.

3.2.4. *29 July 1972* — The Canberra aircraft carried out sorties at different levels along latitude 17°25′N from 73° to 74° E. 3-4 oktas *Sc* and *Cu* clouds were reported by stations around the flight path. The maximum value of albedo recorded during the two portions of the flights was 0.40. The variation with height of the incoming global solar radiation was small. Appreciable changes occurred in the values of reflected solar radiation due to variations in the amount and types of the clouds below. The incoming solar radiation was higher for the flight at the lower level of 4570 m due to higher solar elevation angles.

3.2.5. *1 August 1972* — The values of incoming and reflected solar radiation and albedo relating to a flight on 1 August 1972, when the aircraft was flying low over sea at a height of 150 m, are given in Table 1. Low and medium clouds were above the aircraft with occasional breaks in the cloud cover as will be seen from the fluctuations in the global radiation. Reflected solar radiation was very low, ranging between 0.02 to 0.05 cal/cm^2/min. The angle of elevation of the sun increased from 24° to 38° during the flight. The higher values of albedo over the sea are due to low angles of solar altitude.

3.2.6. *27 August 1972* — The aircraft carried out a flight along Lat. 24°N roughly between longitudes 83° and 88° E (Table 1). The flight was at a height of 4900 m. There was cirrus above and throughout the flight 6 to 7 oktas of stratocumulus was present below the aircraft. The aircraft was about 60 m above the top of the cloud layer. The clouding was more extensive during the first half of the flight. The variations in the incoming solar radiation was attributable to the presence of thin cirrus above the aircraft. The incoming radiation varied between 1.36 cal/cm^2/min to 1.62 cal/cm^2/min, during the flight with an average value of 1.5 cal/cm^2/min. There were large changes in the values of reflected solar radiation and albedo due to the clouds below. The maximum value of reflected solar radiation recorded was 0.83 cal/cm^2/min and the albedo 0.60. The variations in the reflected solar radiation and albedo were due to variations in the thickness of the cloud layer below, low values corresponding to a thinning or

TABLE 3

Albedo of earth's surface and of clouds near Poona — DC-3 Flights

Date (1973)	Solar radiation Global (cal/cm²/min)	Reflected	Flight level amsl (m)	Time (IST)	Solar elevation (degrees)	Surface type	Albedo	Remarks
29 Oct	1·23	0·21	1830	1430	44	Brown soil plus 30 %green fields	0·17	No cloud
	1·00–1·27	0·16–0·20	1830	1432–1438	44–43	30 %brown soil plus 70 % green fields	0·14–0·19	Small patches of *Cu* above
	0·54–0·98	0·07–0·11	1830	1440–1445	43–42	50 %green fields rest brown soil	0·11–0·20	*Cu* clouds above
	0·67–1·24	0·06–0·10	1220	1450–1455	41–40	80 %green fields rest brown soil	0·08–0·10	*Cu* patches above occasionally
	0·82–1.08	0·10–0·12	1220	1458–1501	39–38	Do.	0·12–0·14	Do.
	0·20–0·54	0·04–0·08	1220	1538–1542	31–30	Do.	0·11–0·22	*Cu* clouds above
	0·20–0·86	0·03–0·12	1220	1544–1549	30–29	90% green fields rest brown soil	0·10–0·15	Do.
	0·20–0·80	0·02–0·10	1220	1552–1557	28–27	Do.	0.10–0·12	Do.
	0·15	0·03	1220	1622	22		0·20	*Cu* above and aircraft inside *Cu*
	0·12–0·17	0·01–0·02	1220	1639–1644	18–17	70–90 % green fields rest brown soil	0·08–0·14	*Cu* 8 oktas and thin *Sc*
	0·18–0·21	0·02–0·03	1220	1659–1704	14–13	80% of green fields	0·12–0·16	No cloud above
30 Oct	0·42	0·19	1520	1610	24		0·45	Aircraft inside *Cu*
	0·71–0·76	0·17–0·16	1520	1611–1613	24–23	50% green fields rest brown soil	0·21–0·24	No cloud above
	0·42	0·14	1520	1615	23		0·33	Aircraft inside *Cu*
	0·43–0·57	0·09–0·10	1520	1621–1625	22–21	60% green fields rest brown soil	0·17–0·21	*Cu* cloud above occasionally
	0·52–0·62	0·07–0·15	1520	1626–1630	21–20	90% green fields rest brown soil	0·11–0·28	No cloud above
	0·48–0·50	0·07	1520	1633–1636	19–18	Do.	0·14–0·15	No cloud
	0·35–0·41	0·05–0·07	1520	1642–1646	17–16	Do.	0·13–0·19	Do.
	0·32–0·39	0·04–0·06	1520	1654–1658	14–13	Green fields	0·10–0·17	Do.
	0·27–0·29	0·04–0·05	1520	1701–1706	13–12	90% green fields rest brown soil	0·15–0·21	No cloud above
	0·15–0·21	0·02–0·04	1520	1718–1723	9–7	Green fields	0·13–0·19	Do.

the absence of clouds below the aircraft. Although information on the thickness of the stratocumulus below the aircraft is not available, the above measurements would suggest that on the average the albedo of *Sc* is of the order of 0.35.

3.3. *Individual DC-3 flights*

Two flights were made from Poona to Khedgaon 50 km to the east of Poona on 29 and 30 October 1973. The values of the global and reflected solar radiation and albedo for the underlying surface measured during level flights from Khedgaon to Nahvre 20 km apart are given in Table 3.

On 29 October 1973, at a height of 700 m global solar radiation which was of the order of 1.22 cal/cm²/min, with blue skies above, fell to 0.54 cal/cm²/min when the aircraft entered cumulus cloud. Large variations in global radiation were observed, while the reflected solar radiation from the ground, mostly brown soil with vegetation varying from 30 to 90 per cent, was more or less constant at 0.08 cal/cm²/min, ranging from 0.05 to 0.1 cal

TABLE 4

Mean values of albedo for principal types of clouds over India, land and sea

Cloud type	Albedo at different aircraft altitudes between			Albedo of clouds just below aircraft
	3·0–4·5 km	5·0–7·5 km	12·0–15·0 km	
Active Cumulus	0·20–0·69	0·31–0·43	0·18–0·45	0.50–0.80
Smaller Cumulus	0.25–0·40	0·16–0.43	0·14–0.22	0·44–0·69
Stratocumulus	0·19–0·34	0·15–0·44	0·10–0.34	0·35–0·39
Stratus	0·15–0·22	0·15–0·25	—	—
Altocumulus	0·22–0·30	0·26–0·28	—	0·35–0.43
Altostratus	0·26–0·36	0·16–0·69	0·14–0·16	0·36–0·39
Cirrus top of Cumulonimbus	—	—	0·28–0·46	0·31–0·46
Cirrostratus	—	—	0·21-0·31	0·26–0·39
Type of underlying surface				
Land	0·14–0·19	—	0·11–0·13	
Sea	0·11–0·13	0·08–0·16	0·02–0·06	0·07–0·16 (at 0·15 km)

cm^2/min. Albedo varied very little for brown soil with 30 per cent grass to an underlying cover of 90 per cent green grass.

4. Cloud reflectance

The term albedo, if not qualified, is used in the present discussions for the ratio of the total upward flux to the total downward flux as measured at the aircraft. Cloud reflectance or the albedo of a cloud layer is therefore really the albedo of the material layer below the aircraft or the vertical system consisting not only of the cloud mass in question but also the underlying land/sea surface and the intervening clear air with haze and lower cloud layers. For example, if the true albedo of a continuous cloud layer is 0.45 over a surface albedo of 0.15 separated by dust-free air, the measured value above but near the cloud top will approach 0.50, on account of part of the upward ground/air reflected radiation penetrating the cloud. If there are breaks in the cloud, the measured albedo will be too high or too low depending on the component albedos of the system. It is difficult to apply such corrections and assign the correct albedo to each type of cloud, without knowing its thickness or water content. The relatively high speed sampling possible from the jet aircraft equipped with sufficiently rapid response radiation detectors thus provide large scale rather than local cloud reflectances.

In Table 4 is summarised a selection of the albedo measurements for the principal cloud types, cumulus, stratocumulus, stratus, altocumulus, cirrus and cirrostratus over Peninsular India during the monsoon months July and August. No corrections have been applied for the influence of the underlying surface and the effect of atmospheric scattering. However, it is known that for a general aircraft height of about 10 km, the total albedo of a calm sea surface (*e.g.*, 1 m waves), under a cloudless sky with a high sun (approximately 75°) and little haze, increases from about 0.03 (measured at about 300 m altitude) to about 0.05(Drummond and Hickey 1971). This would have the effect of introducing an error generally of only about +0.01, with the cloud albedo at the higher altitude. With haze conditions and scattered cumulus below, the water/air (haze) value increased to 0.08-0.09 at 10 km which would roughly double the correction indicated above. Over land, with cloudless sky and moderate haze or none, the high level albedo was about 0.10-0.25 compared to the value of 0.15 obtained by Drummond and Hickey (1971). This would yield a correction of the order of 0.03.

Meteorological Research Flight aircraft of the British Meteorological Office had made similar observations of solar radiation fluxes in the atmosphere during 1958-60 from a Canberra aircraft over southern England and over the

TABLE 5

Comparison of cloud albedo values

Cloud type	India	Vonder Ha r and Cox (1972)	Drummond and Hickey (1971)	London (1958)			Robinson (1959)	Conover (1965)
				Max	Min	Av.		
Cu	0·25–0·40	0·50–0·55	0·56	0·70	0·70	0·70		0·29
St Sc	0·40–0·60	0·35–0·42	0·47	0·56	0·65	0·60		
Ac As	0.70–0·40	0·35	0·40	0·48	0·52	0·50		
Ci Cs	0·15–0·35		0·20	0·26	0·20	0·23		0·32–0·36
Sc Cu	0·22–0·70						0·29–0·42–0·56–0·87	0·69
Sc	0·15–0·44						0·48–0·83	0·68
Ns							0·64–0·70	
Fs	0·15-0·25						0·51	
Sea	0·04-0·13						0·07–0·12	0·07–0·09
Land	0·10-0·25						0·12–0·25	

Sahara Desert and Equatorial East Africa (Roach 1961). The high level measurements of the albedo of the earth and the atmosphere gave individual values of albedo which ranged from 0.05 over sea and 0.15 over land on a clear day to 0.85 over a troposphere filled with cloud. Visual and total albedo were observed to be greater than that computed for a Rayliegh atmosphere.

The extensive aircraft observations made over the continental areas of the U.S.S.R. (Barashkova *et al.* 1961) from an altitude of about 500 m show that albedo values are practically identical for similar surfaces under similar observational conditions. The albedo of various surfaces calculated from satellite data by Conover (1965) also shows the wide limits of albedo variation over an area.

Table 5 presents for comparison purposes, cloud albedo values obtained from theoretical calculations by London (1958), and from aircraft observations by Robinson (1959) and by Drummond and Hickey (1971) over the Caribbean during BOMEX. Mean albedo values of various cloud types as determined from the brightness of cloud cover TV pictures by Conover (1965) are also included. London's data on minimum albedo refer to mean summer and autumn conditions in low latitudes, and maximum to mean winter and spring conditions in high latitudes. Robinson's results relate to low solar heights (10-34°) while Drummond's relate to high solar elevations (65° average). Robinson(1959) obtained a mean value of 60 per cent for clouds, whose value varied within 29-87 per cent. Timerev (1965) has given an albedo of 70-75 per cent for clouds 1.5 km thick, with any type of underlying surface, while Koptev (1961) obtained an albedo of 68 per cent for overcast conditions (*Sc, St, Ns*). Cloud albedo suggested by Houghton (1964) was 69, 48 and 21 per cent for low, middle and high clouds. The cloud albedo for the effective cloud as taken by Godbole *et al.* (1970) is 48 and for monsoon clouds 55.

The values of clouds albedo obtained over India are in fairly good agreement with those obtained elsewhere except for cirrus for which they are higher. The albedo of clouds depends on the form and thickness of clouds, solar elevation and, with small cloud density, on the underlying surface albedo as well. The greatest albedo variations associated with changes in cloud thickness refer to observations over surfaces with small albedo. The albedo of clouds increases with an increase both of cloud thickness and its water content. The dependence of the albedo of clouds on the solar height is most spectacular for thin clouds (120-210 m) and low total water content.

5. Planetary albedo

An important component of the earth's radiation budget on planetary or regional scales is the albedo of the earth-atmosphere system. It has been directly measured on a global scale since the first TIROS satellite was launched in 1960. Indirect measurements and theoretical and other considerations based on meteorological computations had given in the past, values ranging from 0.33 to 0.43 for the planetary albedo (Ångström

1962). Nimbus II satellite measurements (Raschke *et al.* 1973) found the global albedo to be about 30 per cent considerably less than the earlier accepted values between 33 and 43 per cent. Vonder Haar and Suomi (1969) were the first to notice that the planetary albedo was only 29 to 30 per cent in contrast to the then accepted value of 35 per cent. They also found the same albedo for both northern and southern hemispheres.

Although high altitude aircraft and satellite albedo data are not strictly comparable, comparisons have been made between simultaneous Nimbus III satellite and aircraft albedo data below, by Drummond and Hickey (1971) and by Vonder Haar and Suomi (1969) in the tropical latitudes in the Caribbean during BOMEX. With a cloudless sky above and scattered *Cu* below and sometimes haze, the mean total albedos for integral short wave lengths was found to be 0.082 as given by the aircraft at 11 km and 0.089 as given by the satellite.

A specially co-ordinated programme using research aircraft and the geostationary satellite ATS-3 during BOMEX also enabled simultaneous measurements of solar radiation within and emerging from the heterogeneous tropical atmosphere over the Caribbean. The results which give low values of albedo over the tropics, indicate greater absorption than expected due to turbidity in the lower atmosphere (Vonder Haar and Cox 1972).

From Nimbus III data, the planetary albedo of dense convective cloud mass in the ITCZ in the Caribbean was found to be 52 per cent. The albedo of altostratus with some cirrus was found to be 30 per cent while the aircraft gave 35 per cent at 18,000 ft over the Caribbean on 18 July 1973.

In tropical and subtropical latitudes of both hemispheres, the albedo changes due to the movment of the ITCZ and the Asian monsoon cloudiness. Over India the albedo is about 30 per cent over east Central India and 20 per cent elsewhere. Over the Himalayas it exceeds 30-40 per cent Over the Arabian Sea it is 15-20 per cent and over the Bay of Bengal 20-30 per cent.

For comparisons of planetary albedo values with surface measurements 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

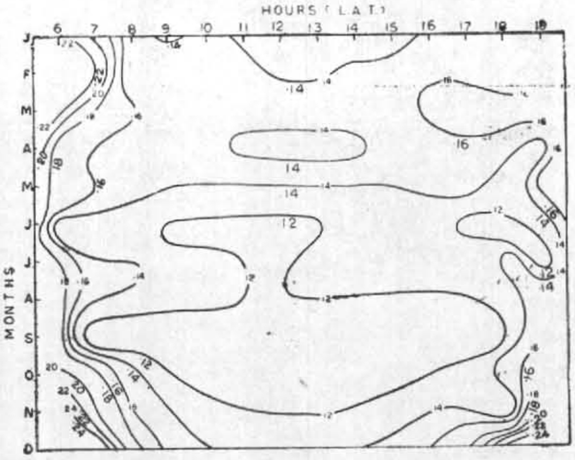

Fig.4. Iscpleths of albedo a Poona showing hourly variation in different months

observations are somewhat higher than those of the earth-atmosphere systen, since at the ground for the most part, only radiation in the spectral range from 0.3 to about 1.5 μm will be observed and where most surfaces will have a higher albedo than the atmosphere for the radiation of longer wave-lengths, which is strongly absorbed by atmospheric gases. Thus Numbus III albedos of 50-70 per cent over snow covered regions do not contradict those of snow and ice measured at the ground to be 75-80 per cent.

Kondratyev *et al.* (1972) have determined the albedo of the underlying surface from satellite albedo measurements using Shefrin *et al.*'s formula (1964). Verifying COSMOS and METEOR satellite data he found agreement within 10 per cent in 260 out of 314 occasions. He found the planetary albedo over Indian Ocean to be 0.13, ranging from 0·08-0.20, while the surface albedo is 0.12, ranging from 0.03 to 0.23. Over 'Hindustan' they found both planetary and surface albedo to be the same 0.18 (0.15-0.21).

6. Surface albedo

Extensive information on the albedo of the earth's surface over different kinds of underlying surfaces, over soils and bare surfaces, over vegetative covers and snow cover, over water basins and the sea is available, for various regions of the earth. The surface measurements are made at a height of 1.5 metres above the level of the underlying surface and consequently characterise reflective properties of small areas. Surface albedo measurements over a bare soil surface were started at Poona in 1963, and have been continued on a regular basis since then with additional observations from New Delhi from 1972. Albedo has also been measured at different places and over different surfaces in and around

TABLE 6

Mean monthly values of albedo at Poona

Month	Hours (LAT)														
	5-6	6-7	7-8	8-9	9-10	10-11	11-12	12-13	13-14	14-15	15-16	16-17	17-18	18-19	Mean
						1963									
Dec	·26	·19	·15	·14	·14	·14	·14	·14	·14	·15	·16	·17	·24		·17
						1964									
Jan		·20	·15	·13	·14	·13	·13	·13	·13	·13	·14	·14	·14		·14
Feb		·22	·15	·14	·14	·14	·13	·13	·14	·14	·15	·15	·14		·15
Mar		·18	·16	·15	·14	·14	·14	·14	·14	·15	·16	·16	·16		.15
Apr	·17	·16	·14	·14	·14	·13	.13	·13	·13	·14	·14	·15	·15	·14	.14
May	·17	·16	·15	·14	·14	·14	·14	·14	·14	·14	·15	·15	.14	·16	.15
Jun	·13	·13	·13	·12	·12	·12	·12	·12	·13	·13	·13	·12	·12	·13	.13
Jul	·20	·14	·14	·13	·13	·12	·12	·13	·13	·13	·13	·13	·14	·12	.10
Aug		·14	·13	·13	·13	·12	·12	·12	·12	·12	·12	·12	·13	.09	·11
Sep		·11	·11	·11	·11	.11	·11	·11	·11	·11	·12	·12	·12		·12
Oct		·19	·14	·12	·11	·11	·11	·11	·11	·12	·12	·13	·15		·13
Nov		·20	·16	·14	·13	·12	·12	·12	·12	·13	·14	·14	·13		·14
Mean	·19	·17	·14	.13	·13	·13	·13	·13	·13	·13	·14	·14	·15	·13	·14

Poona, Delhi and in Gulmarg and Khilanmarg in Kashmir. These values are compiled in Table 7, while the mean monthly values of albedo at Poona for the two years 1963-64 are given in Table 6 and the isopleths of albedo of the natural underlying surface at Poona in Fig. 4.

The diurnal variation of the albedo is influenced by surface roughness and irradiation conditions, such as the solar elevation, the relation between scattered and global radiation as well as the variations in the spectral-composition of incident radiation. Fig. 4 shows that albedo is a minimum at noon and increases with a decrease in solar elevation, in agreement with observation and theoretical calculations by other workers.

The albedo of a particular kind of soil is subject to variations, depending on its colour, structure and humidity. Thus during the monsoon months at Poona, surface albedo values show a marked fall from 0.17 to 0.10.

The values are in good agreement with the aircraft values given in Tables 2 and 3, 5 and 6.

7. Albedo of the sea

The average value of the albedo of the sea from aircraft measurements over the Arabian Sea, Bay of Bengal and the Indian Ocean immediately to the south of the tip of the Peninsula measured from the Canberra aircraft is about 0.02 to 0.16 for solar elevation angles of 22° to 81°.

Earlier aircraft measurements of the sea surface albedo are summarised in Table 7 with the Indian data. The importance of solar elevation

TABLE 7

Albedo measurements cover different surfaces at Poona, Delhi, Gulmarg and Khilanmarg

Type of ground surface	Angle of Sun's elevation (degrees)	Albedo	Earlier measurements (Kondratyev 1969)
	Poona		
Dry tall grass	85	0·25	0·18–0·20
Green grass	85	0·21–0·24	0·26
Dry grass	79	0·20	
Ash gray soil	87	0·20	
Groundnut field	73	0·18	
Sugarcane crop	82	0·15	
Gray soil	46	0·15	0·25–0.30
Black cotton soil	56	0·10	
	New Delhi		
Green grass	61	0·23	0·26
Green dwart grass	55	0·24	
	Pashan		
Green grass	82	0·23	
Dry reeds	85	0·25	
	Gulmarg		
Wet green grass	30	0·28	
Dry grass	59–76	0·23	
	Khilanmarg		
Dirty dull snow	55–69	0·41–0·50	
Clear bright but old snow	75–79	0·59–0·63	

and sea surface conditions such as wave heights bubbles, both at and below the surface, water, turbidity etc on albedo are well known. The albedo of a water layer either smooth or roughened by wind (but not to the point of having breaking waves, white caps, large quantities of bubbles etc) has a remarkably constant value for any given solar elevation and clear sky conditions. However, the formula given by Anderson (1952) based on Lake Hefner measurements relating albedo with solar elevation cannot be extrapolated to rough ocean environments as done by Deacon and Stevenson (1958) for the Indian Ocean. Nor can average values of albedo such as those given by Budyko (1958) be used for short-duration studies or for extended periods for which high sea states prevail.

8. Conclusions

The albedo of sea and land surfaces and the albedo of clouds for solar radiation have been measured from aircraft flying at levels from 150 to 15,000 m above the underlying surface over the Indian subcontinent and the adjoining seas during the monsoon season July to September. The results give reflectance data for the first time over extensive areas of the Indian subcontinent over soil, vegetation, water basins and the sea. The results are in good agreement with values obtained by workers at other latitudes and with satellite measurements of the planetary albedo and surface observations in India of the albedo near the ground.

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