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Solar radiation measurements and studies of atmospheric transmission at high altitude stations in India

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ABSTRACT. Results of radiation measurements made at high altitude stations in the Himalayas and other locations in India have been studied. The values of direct solar radiation at stations in Kashmir during the pre-monsoon summer months are exceptionally low and lower than those at Kodaikanal inspite of low atmospheric humidity. Such exceptionally low values of direct solar radiation observed in Kashmir have to be attributed to the thick layer of aerosols over most of north India during the summer months. Values of atmospheric turbidity were found to be comparatively high over the Himalayas. Spectral measurements of direct solar radiation as well as global and diffuse solar radiation at the high altitude stations have been discussed.

1. Introduction

The study of the radiation climate of India will be incomplete without a knowledge of the radiation parameters over the Himalayas. The national radiation network does not include a station in the Himalayas measuring the various components of radiation. Besides, the values of radiation in the Everest region obtained during the Everest Expeditions of 1961 and 1963 were surprisingly low contrary to expectations. Measurements of radiation components at high-altitude stations are important for the study of turbidity parameters and of the attenuation of solar radiation in the atmosphere. A programme of solar radiation measurements was organized in June 1969 at a number of high altitude stations in Kashmir, at Gulmarg (2702 m), Khilanmarg (3224 m) and Al Pathar (3685 m). Observations of global solar radiation were also made during a scientific expedition to Gangotry at Gaumukh (3920 m) and Rakta Varna Glacier (4910 m) and Kirti Glacier (4910 m) during September-October 1971. Direct solar radiation measurements were also made during Nun Kun (4720 m) Expedition 1972 by Geological Survey of India and the Gara Glacier (4500 m) Expedition 1974. The present paper summarises the results of these observations and discusses the atmospheric transmission over these stations.

2. Instruments and Observations

2.1. *Radiation measurements in Kashmir*

2.1.1. *Observation sites* — At Gulmarg the observational site in front of the High Altitude Research Laboratory, was located in a green meadow sloping slightly towards the east at a height of 2702 m (Lat. 34° 03′N, Long. 74° 24′E). The Gulmarg valley is in the form of a shallow bowl and the observational site was located on the western side of the bowl. During the period of observations, the skies were clear, though somewhat hazy in the forenoon, becoming cloudy in the afternoon. It rained on two days towards the evening. It was generally calm in the mornings with the wind rarely above 8 km/hr. Temperatures ranged between 5° and 20° C. About 6 km west of and 610 m above Gulmarg valley is Khilanmarg at a height of 3224 m. Khilanmarg lies above the tree line and the ground was partly covered with snow. The wind speed ranged from calm to 8 km/hr. On the two days of observations at Khilanmarg it was clear in the mornings but became cloudy in the afternoons. Above Kihlanmarg is Apharwat, a ridge 4420 m a.s.l. and Al Pathar lies to the west of Khilanmarg at a height of 3685 m. During observations the ground was completely covered with snow except for a few spots on projecting rocks. Wind speed was of the order of 12-20 km/hr.

TABLE 1

Values of global(G), diffuse (D) and reflected (R) Solar radiation, net radiation (N) and albedo (α) at Gulmarg

(Lat. 34°03′N; Long. 74°24′E, Altitude : 2702 m above sea level)

Date (Jun 69)	Time LAT	G (cal/cm²/min)	D (cal/cm²/min)	R (cal/cm²/min)	D/G	α = R/G	G—D (cal/cm²/min)	G—R (cal/cm²/min)	N	Condition of ground	Condition of sky
12	0558	·303	·063	·114	·208	·376	·240	·189	·039	Green wet grass	Clear
	0603	·333	·064	·121	·192	·363	·269	·212	·061	,,	
	0628	·461	·069	·148	·150	·321	·392	·313	·143	,,	
	0658	·607	·080	·180	·132	·297	·447	·427	·239	,,	
	0728	·809	·090	·223	·111	·276	·719	·586	·377	Sl. wet grass	Clear
	0758	·953	·103	·244	·108	·256	·850	·709	·482	,,	Sun free, Cu_1
	0828	1·087	·127	·271	·117	·249	·960	·816	·585	Grass dry	Sun free, Cu_2
	0853	1·287	·224	·315	·174	·245	1·063	·972	·703	,,	Cloud near sun, Cu_2, Sc_1
	0958	1·663	·425	·400	·256	·241	1·238	1·263	1·036	,,	Sun free, Sc_4, Cu_1
	1013	1·711	·444	·405	·259	·237	1·267	1·306	1·037	,,	,,
	1028	·610	·541	·139	·890	·228	·067	·471	·327	,,	Sun behind clouds Cu_4, Sc_2
	1103	1·605	·255	·364	·159	·227	1·351	1·241	·977	,,	Sun free, Sc_4 Cu_1
	1128	2·085	·763	·466	·366	·223	1·322	1·619	·956	,,	Sun free, Sc_4, Cu_2
	1158	—	·613	—	—	—	—	—	1·261	,,	Cloud near Sun, Sc_4, Cu_2
	1228	1·961	—	·445	—	·227	—	1·516	—	,,	Sun free, Cu_2, Sc_5, thunder heard
	1248	1·965	—	·452	—	·230	—	1·513	—	,,	,,
	1305	2·000	—	·459	—	·229	—	1·451	—	,,	Sun free, Cu_2 Sc.
	1325	·834	·516	·305	·619	·365	·318	·529	—	,,	Cloud near sun, Cu_4, Sc_2
	1352	1·589	·457	·359	·287	·226	1·132	1·230	·937	,,	Sun free, Cu_4, Sc_2
	1420	1·439	·393	·324	·273	·225	1·046	1·115	—	,,	Cloud near sun, Cu_4, Sc_1
	1455	1·214	·187	·161	·154	·133	1·027	1·053	·673	,,	Cloud near sun Cu_3
	1528	1·032	·125	·125	·121	·121	·907	·907	·547	,,	Sun free, Cu_2, Sc trace
	1558	·891	·128	·211	·143	·237	·763	·681	·448	,,	Sun free, Cu_1, Cb_1, Sc tr
	1643	·631	·091	·153	·145	·243	·539	·477	·267	,,	Sun free, Cu tr
	1710	·496	·083	·125	·168	·252	·413	·371	·189	,,	Sun free, Cu tr, Sc tr
	1741	·323	·073	·083	·225	·257	·250	·239	·083	,,	,,
	1805	·186	·057	·047	·304	·253	·129	·139	·008	,,	Sun free, Cu tr
13	0728	·697	·131	·198	·188	·284	·565	·499	·349	Wet grass	Clear sky
	0843	1·073	·156	·270	·145	·252	·917	·803	·608	Dry grass	Sun clear, Cu_1
	0948	1·333	·172	·315	·129	·256	1·161	1·018	·771	,,	Sun clear, Cu_2
	1038	1·487	·253	·341	·170	·229	1·234	1·146	·911	,,	Sun clear, Cu_1 Sc_2
13	1148	1·644	·233	·363	·141	·221	1·411	1·281	·983	Dry grass	Sun clear, As_1, Cu_2, Sc_1
	1528	·413	·323	·095	·782	·230	·090	·318	0·43	,,	Sun covered, Cu_1, Sc_2, Cb_1
	1545	·540	·323	·124	·598	·230	·217	·416	·403	,,	Sun covered, Sc tr Cu_1, As_2, Ci_2
	1608	1·053	·253	·255	·240	·241	·799	·798	·051	,,	,,
13	1628	·711	·198	·173	·279	·243	·513	·539	·371	Dry grass	Sun covered, Sc tr Cu_1, As_2, Ci_2
	1710	·171	—	·040	—	·234	—	·131	—	,,	Sun behind clouds, As_3, Cu_1, Ci_1
	1738	·108	—	·028	—	·259	—	·080	·021	,,	,,
	1800	·212	·147	·093	·693	·443	·065	·119	·119	,,	,,
15	0818	·955	·193	·251	·203	·263	·762	·704	·493	Wet grass	Clear sky
	0918	1·201	·213	·291	·177	·243	·988	·909	·665	Dry grass	Sun clear Sc tr
	1028	1·412	·215	·324	·152	·229	1·197	1·088	·813	,,	,,

TABLE 1 (*contd*)

Date (Jun 69)	Time LAT	G	D (cal/cm²/min)	R	D/G	α=R/G	G-D	G-R (cal/cm²/min)	N	Condition of ground	Condition of sky
16	0758	·827	·193	·223	·233	·270	·634	·603	·411	Wet grass	Clear sky
	0853	1·075	·220	·271	·205	·252	·855	·804	·593	,,	Clear but white hazy sky
	0953	1·296	·260	·306	·201	·236	1·036	·990	·748	Dry grass	Sun clear, Hazy sky Cu tr
	1058	1·465	·283	·332	·193	·227	1·182	1·133	·859	,,	Sun clear, Hazy sky, Cu_1
	1148	1·541	·321	·339	·208	·220	1·220	1·202	·919	,,	,,
17	0755	·817	·165	·221	·201	·271	·652	·596	·079	Wet grass	Clear but white sky, Hygroscopic haze
	0856	1·105	·184	·274	·167	·248	·921	·831	·571	,,	,,
	0942	1·287	·221	·301	·171	·234	1·065	·985	·711	Dry grass	Clear sun, Sc tr haze
	1030	1·431	·283	·328	·198	·229	1·148	1·103	·834	,,	,,
	1051	1·495	·320	·336	·214	·225	1·175	1·159	·871	,,	,,
	1125	1·583	·357	·353	·226	·223	1·226	1·230	·891	,,	Cloud near sun, Sc & Cu 8 octa
	1154	1·552	·321	·343	·207	·221	1·231	1·209	·937	,,	Sun clear, Sc_1, Cu tr
	1235	1·592	·357	·352	·224	·221	1·235	1·240	—	,,	,,
	1324	1·576	—	·345	—	·219	—	1·231	·912	,,	Cloud near sun Sc_3, Cu tr
	1413	1·464	—	·339	—	·231	—	1·125	·868	,,	Cloud near sun, Sc_3, Cu_1

2.1.2. *Instrumental equipment* — Measurements were made of the following radiation components : (*a*) Global solar radiation, (*b*) Diffuse solar radiation, (*c*) Direct solar radiation in the whole spectrum and in selected spectral regions, (*d*) Reflected solar radiation, (*e*) Net radiation. Measurements of atmospheric turbidity with the Volz sunphotometer and soil heat flux were also included in the programme.

For the measurement of global, diffuse and reflected solar radiation the Moll-Gorczynski pyranometers were on tubular aluminium supports 1·5 m high. The outputs of the pyranometers were read on a Cambridge portable potentiometer. The same pyranometer was used both for global and diffuse radiation measurements. For reflected solar radiation, a second pyranometer installed at a height of 1·5 m above ground was used.

Direct solar radiation with and without filters was measured using an Angström compensation pyrheliometer with its auxiliary equipment as well as an Eppley normal incidence pyrheliometer and portable potentiometer. Net radiation was measured using Funk net pyrradiometer and Gambridge potentiometer. Standard glass filters OG_1, RG_2 and RG_8 were used for measurements with Angström pyrheliometer and Eppley normal incidence pyrheliometer.

2.1.3. *Observations* — The observations at Gulmarg were started on the 12 June 1969 and continued till the 18 June except for a short break on the 14th. Measurements of all components except direct solar radiation were carried out at hourly or half-hourly intervals on the 12th and 13th throughout the days and on the 15th, 16th and 17th during the forenoons. Measurements of direct solar radiation could be carried out only in the forenoon on all days due to cloudy skies. On the 18 June only direct solar radiation measurements were made. The measurements were made over green grass, which used to remain wet till about 9 in the morning. The surface soil continued to be wet throughout the day.

At Khilanmarg radiation observations were made on the 13th and 14th. Direct solar radiation measurements were carried out on the 13th and observations of direct solar radiation, global radiation and reflected solar radiation on the 14th. Reflected solar radiation observations were conducted over both bare soil and ice.

Observations of direct solar radiation at Al Pathar were made on the 18 June.

2.1.4. *Results of radiation measurements in Kashmir*— The results of measurements made at Gulmarg are given in Tables 1 and 2. The values of global radiation (G), diffuse radiation (D), reflected shortwave radiation (R), albedo (*a*) and the ratio D/G, G—D, G—R, net radiation N, are given in Table 1. Direct solar radiation in the different spectral regions and the values of turbidity coefficient β and transmission coefficient

TABLE 2

Integral and spectral values of direct solar radiation, parameters of atmospheric turbidity and transmission coefficent at Gulmarg (34°03′N, 74°24′E, 2702 m a.s.l.) Measurement with Angstrom pyrheliometer

Date	Time LAT	m	I	I_1	I_3	I_8	$I—I_1$	$I—I_2$	$I_2—I_8$	a	β_0	β	q
			(cal/cm²/min)										
12 Jun 69	0619	2·56	1·067	0·885	0·721	0·602	·182	·346	·119	0·40	·067	·022	·79
,,	0738	1·37	1·305	1·009	0·809	0·658	·296	·496	·151	0·77	·034	·016	·75
,,	0835	1·06	1·336	1·028	0·821	0·668	·308	·515	·153	1·74	·029	·026	·71
13 Jun 69	0759	1·23	1·178	0·928	0·748	0·606	·250	·430	·142	2·29	·044	·056	·67
,,	0903	0·96	1·289	0·996	0·797	0·645	·293	·492	·152	2·50	·027	·047	·66
,,	1007	0·83	1·361	1·036	0·815	0·665	·325	·546	·150	1·08	·068	·027	·66
,,	1057	0·78	1·365	1·038	0·817	0.668	.327	·548	·149	1.14	·075	·030	·65
,,	1225	0·75	1·393	1·064	0·837	0·684	·329	·556	·153	1·81	·046	·023	·65
15 Jun 69	0856	0·98	1·216	0·935	0·746	0·601	·281	·470	·145	1·76	·052	·072	·63
,,	1009	0·83	1·279	0·968	0·774	0·632	·311	·505	·142	0·31	·131	·053	·61
,,	1117	0·76	1·332	0·987	0·782	0·639	·345	·550	·143	—0·16	·165	·030	·62
,,	1208	0·75	1·318	0·987	0·775	0·625	·331	·543	·150	0·56	·117	·036	·61
16 Jun 69	0810	1·17	1·106	0·862	0·684	0·562	·244	·422	·122	0·73	·137	·066	·62
,,	0908	0·95	1·203	0·912	0·724	0·589	·291	·479	·135	0·44	·140	·056	·61
,,	1011	0·82	1·195	0·903	0·717	0·576	·292	·478	·141	1·32	·091	·072	·56
,,	1114	0·76	1·238	0·928	0·731	0·600	·310	·507	·131	0·01	·246	·058	·56
17 Jun 69	0744	1·32	1·123	0·891	0·705	0·568	·232	·418	·137	1·81	·051	·055	·67
,,	0902	0·97	1·239	0·948	0·753	0·606	·291	·486	·147	1·71	·050	·049	·64
,,	1008	0·83	1·261	0·951	0·754	0·620	·310	·507	·134	—0·04	·207	·052	·60
,,	1110	0·78	1·259	0·962	0·759	0·621	·297	·500	·138	1·00	·125	·060	·58
,,	1221	0·75	1·239	0·934	0·736	0·607	·305	·503	·129	—0·09	·282	·062	·56
18 Jun 69	0802	1·21	1·105	0·860	0·700	0·587	·245	·405	·113	—0·04	·219	·072	·63
,,	0841	1·03	1·188	0·923	0·738	0·595	·265	·450	·143	2·09	·047	·048	·63
,,	1019	0·81	1·262	0·952	0·744	0·606	·310	·518	·138	0·42	·149	·047	·59

I : Whole spectrum I_1 : 0·525-2·8μ I_2 : 0·630-2·8μ I_1 : Direct solar radiation with OG_1 filter
I_8 : 0·710-2·7μ I : Direct solar radiation, total I_2 : Direct solar radiatian with RG_2 filter
I_8 : Direct solar radiation with RG_8 filter β : Angstrom turbidity coefficient q : Transmission coefficient
β_0 : Schuepp's turbidity coefficient a : Wave length exponent

q are given in Table 2 with the condition of ground and sky. In Fig. 1 global, diffuse and reflected solar radiation on 12 June 1969 at Gulmarg are plotted. Fig. 1 also represents global and net radiation at Gulmarg on 12 June 1969.

Although the number of occasions when the sky was completely free from clouds was small, the sun itself was free from clouds during most of the observations. It will be seen from Table 1 that a seemingly improbable value of 2 cal/cm²/min was recorded on two occasions around noon with a solar height of 79°. This high value should be attributed to not only multiple reflections from the cloud base, but also to solar radiation reflected by the surrounding hills some of which were partly snow covered. The usual value of global radiation recorded around noon was of the order of 1·65 cal/cm²/min. It is interesting to notice that on occasions when the global radiation was 2 cal/cm²/min the diffuse radiation was 0·76 cal/cm²/min supporting the view that reflections take place from cloud bases and the surrounding hills.

The proportion of diffuse radiation in the global radiation was variable according to the condition of the sky. Usually about 25 per cent of the global radiation was contributed by diffuse radiation.

The value of albedo for the green meadow over which observations were made was of the order of 0·25.

Net radiation reaches a value of 1 cal/cm²/min around noon. This is higher than that normally observed at low level stations, probably due to the increase in incoming radiation due to reflections from cloud bases and hills.

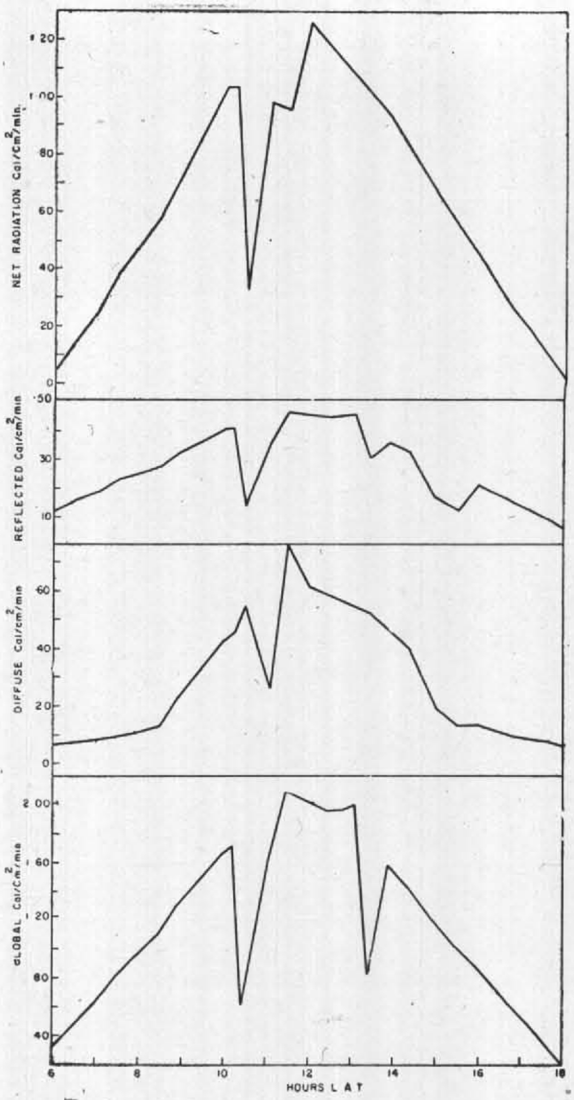

Fig. 1. Variation of global, diffuse, reflected solar and net radiation at Gulmarg on 12 June 1969

Contrary to expectations, the values of direct solar radiation are too low for a high altitude station 2702 m a.s.l. The highest value measured was only $1 \cdot 393$ cal/cm^2/min with an airmass of $0 \cdot 75$, a value comparable to that at Poona 555 m a.s.l. The vapour pressure at Gulmarg is rather low, 8-12 mb and the comparatively low intensity of direct solar radiation must be attributed not to water vapour absorption, but to extinction by aerosols.

The results of measurements made at Khilanmarg (3324 m) are represented in Tables 3 and 4. Table 3 gives values of global radiation, reflected shortwave radiation, albedo and net radiation while Table 4 gives values of direct solar radiation and turbidity. The albedo and net radiation measurements were made over old snow about $0 \cdot 5$ m thick over an area 15 m × 15 m. The values of global radiation are of the same order as those at Gulmarg. The albedo over old snow was $0 \cdot 30$, which increased to $0 \cdot 38$ when the top layers of the snow was removed. Dirmhirn and Trojer (1955) reported higher values of albedo for snow over Alps. The values of intensity of direct solar radiation are slightly higher and turbidity slightly higher and turbidity slightly lower than those at Gulmarg. The highest value of intensity recorded is $1 \cdot 469$ cal/cm^2/min at an airmass of $0 \cdot 71$. The average value of turbidity for 13 and 14 June 1969 is $\cdot 036$. Even here the intensity is lower than that expected at this altitude.

Results of measurements of direct solar radiation and turbidity with an Eppley pyrheliometer

TABLE 3

Values of global (G), diffuse (D) and reflected (R) solar-radiation and net radiation (N) at Khilanmarg

Date	Time LAT	G (cal/cm²/min)	R (cal/cm²/min)	R/G	G—R (cal/cm²/min)	N (cal/cm²/min)	Condition of ground	Sky condition
14 Jun 69	0928	1·368	·413	·302	·955	·853	Dirty dull snow	Cu_1, Sc_{tr}, Cloud near sun
	0957	1·539	·462	·301	1·077	·942	,,	Sc_1, sun clear
	1037	1·647	·504	·306	1·143	1·052	,,	Clouds near sun, Sc_1
	1110	1·636	·587	·359	1·049	·991	Dirty top surface partly removed	Sun clear, Sc_1, Cu_{tr}
	1213	1·584	·618	·390	·966	·907	Clear bright surface, but old snow	Sun clear, Sc_{tr}, Cu_1
	1248	1·574	·627	·399	·947	·954	,,	,,
	1326	1·587	·591	·372	·997	·935	Snow becoming slightly dull	Cb_2, Cu tr, Sc_{tr}, Ac tr, Thunder and distant rain
	1337	·213	·083	·392	·130	·019	,,	Sun covered by thick Cu, Cb_2, Cu tr, Actr.
	1358	·152	·061	·401	·091	·016	,,	Sun covered by thick Cu, Cb_3, Cu_1, Ac tr

TABLE 4

Integral and spectral values of direct solar radiation and atmospheric turbidity at Khilanmarg

(Measurements with Eppley normal incidence pyrcheliometer)

Date	Time LAT	m	I	I_1	I_2	I_8	$I—I_1$	$I—I_2$	$I_2—I_8$	β
			(cal/cm²/min)							
13 Jun 69	0904	0·92	1·377	1·073	0·826	0·721	0·304	0·551	0·105	0·017
	0935	0·85	1·393	1·068	0·849	0·771	0·330	0·549	0·078	0·023
	0954	0·81	1·456	1·151	0·908	0·776	0·305	0·548	0·132	0·026
	1049	0·75	1·456	1·155	0·926	0·789	0·229	0·530	0·137	0·045
	1127	0·73	1·448	1·128	0·931	0·767	0·320	0·517	0·164	0·054
	1205	0·72	1·431	1·105	0·917	0·799	0·326	0·514	0·118	0·056
	1233	0·73	1·436	1·109	0·881	0·767	0·326	0·554	0·114	0·030
14 Jun 69	0951	0·80	1·307	1·018	0·817	0·713	0·289	0·490	0·114	0·061
	0959	0·80	1·348	1·032	0·863	0·712	0·316	0·485	0·151	0·063
	1025	0·76	1·377	1·055	0·853	0·730	0·322	0·524	0·123	0·046
	1041	0·75	1·415	1·082	0·899	0·753	0·333	0·516	0·156	0·051
	1117	0·72	1·398	1·068	0·858	0·739	0·330	0·540	0·119	0·041
	1146	0·71	1·448	1·091	0·885	0·762	0·357	0·563	0·123	0·026
	1215	0·71	1·469	1·091	0·913	—	0·378	0·556	—	0·029
	1255	0·73	1·427	1·041	0·844	0·735	0·386	0·583	0·109	0·013
	1313	0·74	1·440	1·077	0·835	0·739	0·363	0·605	0·096	0·001
Mean										0·036

at Al Pathar are given in Table 5. The intensity of direct solar radiation is higher and the turbidity lower than at Gulmarg and Khilanmarg as expected. But the intensity is still lower than those observed at high altitude stations elsewhere.

2·2. *Observations at Gangotri*

An expedition consisting of twelve scientists carried out hydrological, meteorological and geological studies during September-October 1971 in the Gangotri area in the Tehri-Garhwal district in the Himalayas. Observations of global solar radiation were made at the base camp Gaumukh (30° 56′ N, 72° 04′E, 3920 m a.s.l. and at Rakta Varna Glacier and Kirti Glacier 4910 m a.s.l. A simple bimetallic pyranograph was used to record the global solar radiation and the values recorded given in Table 6.

TABLE 5

Integral and spectral values of direct solar radiation and atmospheric turbidity at Al Pathar

(Measurements with Eppley normal incidence pyrheliometer)

Date	Time LAT	m	I	I_1	I_2	I_8	$I-I_1$	$I-I_2$	I_2-I_8	β
			(cal/cm²/min)							
18 Jun 69	1001	0·72	1·386	1·045	0·863	0·753	0·341	0·523	0·110	0·028
	1032	0·69	1·514	1·160	0·908	0·799	0·354	0·606	0·109	0·001
	1048	0·68	1·473	1·119	0·904	0·785	0·354	0·569	0·119	0·021
	1106	0·66	1·465	1·082	0·844	0·785	0·383	0·621	0·059	—
	1126	0·66	1·498	1·187	0·926	0·794	0·311	0·572	0·132	0·021
	1147	0·65	1·489	1·128	0·895	0·780	0·370	0·603	0·115	0·006
	1210	0·65	1·743	1·055	0·863	0·753	0·418	0·610	0·110	0·002
	1231	0·65	1·473	1·087	0·840	0·735	0·386	0·633	0·105	—
	1258	0·66	1·448	1·000	0·853	0·748	0·348	0·595	0·105	0·009
Mean										0·013

TABLE 6

Measurement of Global Solar Radiation in Gangotry area

Date (1971)	Mean temp.	Daily global radiation (cal/cm²)
Gaumukh Base Camp (3920 m a.m.s.l.)		
24 Sep	—	—
25 Sep	12·6	484
26 Sep	9·2	444
27 Sep	8·5	559
28 Sep	9·3	550
29 Sep	8·4	509
30 Sep	8·7	535
1 Oct	9·2	544
2 Oct	8·7	532
3 Oct	8·8	535
4 Oct	7.7	436
5 Oct	9·3	450
6 Oct	10·0	473
7 Oct	10·2	546
8 Oct	9·0	453
9 Oct	8·8	511
10 Oct	11·3	535
11 Oct	10·4	540
12 Oct	9·0	502
13 Oct	4·4	356
14 Oct	2·4	300
15 Oct	1·1	139
16 Oct	4.6	405
17 Oct	1·5	050
18 Oct	1·2	154
Rakta Varna Glacier (4912 m a.m.s.l.)		
4 Oct	—	—
5 Oct	6·2	505
6 Oct	6·8	473
7 Oct	—	—
Kirti Glacier (4912 m a.m.s.l.)		
9 Oct	—	—
10 Oct	6·0	574
11 Oct	5·5	540
12 Oct	2.0	550
13 Oct	−0·6	466

Constants of instrument at 0°C are: 29.5, 23·3 and 23.3 cal/cm²/ sq. cm for Guamukh Base Camp, Rakta Varna Glacier and Kirti Glacier respectively

The base camp site was surrounded on all sides by high mountain peaks to hieghts of 6800 m. The weather was fine throughout the period of observation from 24 September to 17 October 1971, when very heavy snowfall forced the expedition to abandon the observations and to return to the plains. The maximum global radiation recorded was 574 cal/cm²/day at Kirti Glacier and 559 cal/cm²/day at Gaumukh.

2·3. *Observations at Kodaikanal*

Kodaikanal (2340 m) forms part of the Indian national radiation network and the observations of direct solar radiation and atmospheric turbidity are made with Angström pyrheliometers at the usual synoptic hours of observations. Mean monthly values of direct solar radiation, integrally and spectrally with the Angström turbidity coefficient β and transmisivity are given in Table 7, for the period 1970-1973. The highest values of direct solar radiation are recorded at Kodaikanal 1·595 cal/cm²/min at an airmass of 0·88 compared to the maximum of 1·316 cal/cm²/min at Poona at an airmass of 1·11 and of 1·422 cal/cm²/min at Shillong at an air mass of 1·21. Turbidities are also lower at Kodaikanal than at Shillong and Poona.

2.4. *Observation at Sinhagad*

Observations were also made at Sinhagad (860 m) a flat hill over looking Poona during March 1969. Observations of direct solar radiation were made with an Eppley normal incidence pyrheliometer with the standard GG_{14}, OG_1, RG_2 and RG_8 filters. Simultaneous solar radiation measurements were made at Poona. The values of direct solar radiation, turbidity coefficient and transmisivity are given in Table 8. The values of direct solar radiation are naturally higher and turbidity less at Sinhagad than at Poona. While the sky above Sinhagad is clear, Poona itself is shrouded in a

TABLE 7

Mean monthly values of direct solar radiational (integral and spectral), atmospheric turbidity and transmission coefficient q during 1970-73 at Kodaikanal (10° 14′N, 77°28′E, 2339 m a.s.l.)

	m	I	I_1	I_2	I_8	$I—I_1$	$I—I_2$	$I_2—I_8$	β	q
				(cal/cm²/min)						
0830 IST										
January	1·79	1·428	1·113	·906	·754	·315	·522	·152	·005	·83
February	1·63	1·429	1·235	·897	·731	·294	·532	·168	·006	·83
March	1·48	1·351	1·075	·833	·700	·276	·518	·133	·019	·77
April	1·32	1·308	0·969	·787	·640	·339	·520	·148	·015	·73
May	1·35	1·163	0·901	·703	·566	·262	·460	·137	·037	·68
June	1·37	1·218	0·924	·720	·599	·294	·498	·121	·019	·72
July	1·39	1·283	0·986	·744	·612	·297	·539	·132	·006	·75
August	1·41	1·229	0·940	·750	·600	·289	·479	·150	·027	·71
September	1·37	1·279	0·960	·777	·613	·319	·502	·164	·020	·72
October	1·34	1·351	0·997	·789	·658	·354	·562	·131	·007	·74
November	1·57	1·390	1·069	·857	·704	·321	·533	·153	·008	·78
December	1·67	1·417	1·104	·888	·718	·313	·529	·170	·008	·80
1130 IST										
January	0·93	1·549	1·183	·927	·754	·366	·622	·173	·009	·76
February	0·87	1·550	1·117	·942	·753	·433	·608	·189	·010	·73
March	0·81	1·489	1·117	·879	·719	·376	·610	·160	·016	·69
April	0·79	1·439	1·066	·829	·677	·373	·610	·152	·010	·67
May	0·80	1·281	0·918	·737	·595	·363	·544	·138	·035	·60
June	0·81	1·421	1·038	·809	·660	·383	·612	·131	·004	·68
July	0·80	1·400	1·033	·771	·655	·367	·629	·116	·023	·64
August	0·80	1·255	0·944	·719	·553	·311	·536	·166	·041	·58
September	0·79	1·414	1·028	·827	·663	·386	·587	·164	·013	·66
October	0·83	1·492	1·123	·868	·702	·369	·624	·166	·005	·65
November	0·91	1·499	1·136	·835	·733	·363	·664	·102	·013	·68
December	0·94	1·516	1·139	·918	·734	·377	·597	·184	·017	·69
1430 IST										
January	1·08	1·523	1·158	·917	·753	·365	·606	·164	·003	·78
February	0·99	1·495	1·163	·899	·741	·332	·596	·158	·008	·73
March	0·94	1·491	1·056	·830	·682	·345	·571	·148	·026	·68
April	0·91	1·400	1·000	·820	·664	·400	·580	·156	·015	·69
May	0·93	1·291	0·970	·771	·590	·321	·520	·179	·026	·63
June	—	—	—	—	—	—	—	—	—	—
July	0·92	1·302	0·975	·756	·627	·327	·546	·129	·021	·65
August	—	—	—	—	—	—	—	—	—	—
September	—	—	—	—	—	—	—	—	—	—
October	0·99	1·427	1·062	·833	·667	·365	·594	·166	.001	.71
November	1·14	1·495	1·131	·883	·711	·364	·612	·172	·008	·77
December	1·13	1·463	1·120	·901	·731	·343	·562	·170	·018	·75
1730 IST										
January	2·51	1·282	1·006	·809	·677	·276	·473	·132	·008	·84
February	2·25	1·288	0·961	·792	·634	·327	·496	·158	·009	·80
March	2·09	1·103	0·820	·697	·538	·283	·406	·159	·027	·75
April	2·97	1·030	0·820	·650	·500	·210	·380	·150	·010	·79
May	—	—	—	—	—	—	—	—	—	—
June	—	—	—	—	—	—	—	—	—	—
July	3·05	0·937	0·698	·591	·468	·239	·346	·123	·005	·79
August	—	—	—	—	—	—	—	—	—	—
September	—	—	—	—	—	—	—	—	—	—
October	—	—	—	—	—	—	—	—	—	—
November	2·77	1·232	0·942	·783	·635	·290	·449	·148	·001	·83
December	2·63	1·241	0·961	·783	·619	·280	·458	·164	·004	·82

TABLE 8

Values of direct solar radiation, atmospheric turbidity β and transmission coefficient q at Poona and Sinhagad

Measurements with Eppley N.I. pyrheliometer					Measurements with Angstrom pyrheliometer				
Time LAT	m	I (cal/cm²/min)	β	q	Time LAT	m	I (cal/cm²/min)	β	q
		Sinhagad					**Poona**		
0920	1·21	1·415	·023	·75	0945	1·21	1·338	·041	·72
0949	1·11	1·469	·023	·76	1029	1·10	1·392	·028	·72
1000	1·07	1·490	·014	·76	1123	1·02	1·378	·022	·69
1019	1·01	1·498	·019	·75	1223	1·01	1·305	·042	·66
1048	·98	1·502	·012	·75	1340	1·11	1·195	·090	·63
1102	·96	1·494	·003	·74	1427	1·26	1·157	·075	·65
1119	·94	1·481	·011	·73	1529	1·65	1·060	·065	·68
1252	·95	1·436	·000	·71					
1318	·98	1·461	·000	·73					
1348	1·04	1·358	·037	·69					
1402	1·08	1·328	·024	·69					
1418	1·13	1·344	·021	·70					
1447	1·25	1·303	·021	·71					
1501	1·32	1·224	·038	·69					
1518	1·43	1·245	·0J0	·72					

TABLE 9

Values of direct solar radiation I (cal/cm²/min) and transmission coefficient q during Nun Kun Expedition in 1972

Place	Lat.	Height (m)	Date	Time LAT	Air-mass (m)	I	q (%)	Sky condition
Kishtwar	33°19′N	1655	12 Jun 72	0935	0·75	1·40	66	Clear sky
Yordu	33°41′N	2270	18 Jun 72	0933	0·65	1·40	63	,,
				1133	0·55	1·43	59	Partly cloudy
				1733	1·77	0·84	63	,,
Chillung glacier	33°55′N	4120	29 Jul 72	0758	0·80	1·32	63	Clear sky
				1658	1·15	0·95	54	Partly cloudy, drizzle between 15 & 17 hr
			31 Jul 72	0758	0·80	1·01	45	Partly cloudy
				1658	1·17	1·15	66	,,
			1 Aug 72	0758	0·80	1·26	59	,,
			2 Aug 72	0758	0·81	1·32	63	Clear sky
				1658	1·18	1·15	65	,,
			3 Aug 72	1658	1·19	1·09	62	,,
			5 Aug 72	0758	0·82	1·32	63	,,
Nun Kun	33°57′N	4720	11 Aug 72	0859	0·58	1·66	77	,,
				1159	0·44	1·71	76	Partly cloudy
				1530	0·57	1·60	72	,,

pall of dense white haze and is not visible from Sinhagad in the afternoon. This is reflected in a slight increase in turbidity at Sinhagad also in the afternoon.

2·5. *Observations at Nun Kun*

Measurements were made during the summer of 1972 at Chillung Glacier (4120 m) and Nun Kun (7135 m) by the scientists from the Geological Survey of India. No measurement could, however, be made right at the top of the Nun Kun peak (7135 m) but observations were taken at the Base Camp (4720 m) of Nun Kun. Moll thermopile pyrheliometer was used to measure the direct solar radiation. Measurements were made at different heights on different days from 2270 m onwards. The values

TABLE 10

Values of direct solar radiation I (cal/cm²/min) and transmission coefficient q during Gara Glacier Expedition in 1974

Place	Lat.	Height (m)	Date	Time LAT	Air-mass m	I	q (%)	Sky condition
Morang	31°30′N	2250	13 Sep 74	0911	1·16	1·23	67	Clear sky
				1141	0·87	1·35	65	,,
				1416	1·03	1·25	65	,,
Gara Glacier Base Camp	31°30′N	4430	19 Sep 74	1133	0·69	1·61	76	Clear sky
				1425	0·85	1·39	67	2/8 Sc
			20 Sep 74	1121	0·70	1·52	69	2/8 Sc, 2/8 Cu
			21 Sep 74	1200	0·69	1·52	69	2/8 Sc, 1/8 Cu
			22 Sep 74	0914	0·94	1·57	79	1/8 Sc
				0945	0·85	1·45	70	,,
				1230	0·74	1·54	72	2/8 Sc, 1/8 Cu
Glacier Camp	31°30′N	4500	23 Sep 74	1121	0·69	1·54	70	Traces of cumulus cloud
				1137	0·68	1·54	70	1/8 Cu
				1157	0·68	1·54	70	,,
				1210	0·68	1·54	70	,,
				1223	0·68	1·54	70	2/8 Cu

TABLE 11

Summary of solar radiation measurements on high mountains

Observer	Year	Place	Latitude (°N)	Altitude (m)	I_{max} (cal/cm²/min)	Airmass	Turbidity β
IMD	1969-73	Poona	18·5	555	1·32	1·11	0·04-0·13
IMD	1969-73	Shillong	25·6	1500	1·42	1·21	0·00-0·08
IMD	1972-73	Kodaikanal	10·2	2340	1·60	0·88	0·00-0·04
IMD	1969	Gulmarg	34·1	2702	1·39	0·75	0·02-0·07
IMD	1969	Khilanmarg	34·1	3224	1·47	1·09	0·036
IMD	1969	Al Pathar	34·1	3685	1·51	1·16	0·013
Abbot	1908-10	Mt. Whitney	36·6	4420	1·63-1·66	0·73-0·65	—
USWB	1959-62	Mauna Loa	19·5	3380	1·75-1·68	0·84-0·69	0·010-0·020
Bishop	1961	Silver Hut	27·8	5710	1·65	0·54	0·045-0·050
GSI	1972	Nun Kun	33·9	4720	1·71	0·44	—
IMD	1974	Gara Glacier	31·5	4500	1·57	0·94	—

obtained are given in Table 9. Only at the height 4720 m did the value increase appreciably to 1·60 cal/cm²/min and above.

2·6. *Observationsat Gara*

The direct solar radiation measurements were again taken during the Expedition to Gara Glacier (4500 m) of the *Sutlej* river basin during September 1974. A Moll thermopile pyrheliometer was used in these measurements. The values obtained during this expedition are given in Table 10.

3. Results

3·1. *Direct solar radiation*

Table 11 gives a summary of direct solar radiation measurements made at various high altitude stations in India. An examination of the Table 11 shows that the values of direct solar radiation in Kashmir are unexpectedly low, considering its altitude. Values of direct solar radiation at Mauna Loa, Mount Whitney and the Everest region are included in the table for purposes of comparison. They are higher but remarkably of the same order of magnitude, in spite of the variations in height from 3380 to 5710 m. The low values in the Himalayas compared to those over Mauna Loa and Mount Whitney are obviously the result of the depletion of the incoming radiation by the dense layer of dust which lies over north and central India in the pre-monsoon summer months and extends to 6 km or more into the atmosphere. This was visually observed by Mr. C. P. Vohra, one of the Indian scientists who climbed Mount Everest in 1965. The maximum value observed is 1·393 cal/cm^2/min for an airmass of 0·75 at Gulmarg; 1·47 cal/cm^2/min for an airmass of 1·09 at Khilanmarg and 1·51 cal/cm^2/min for 1·16 airmass at Al Pathar and 1·71 cal/cm^2/min for an airmass of 0·44 at Nun Kun Base Camp. The highest value, recorded, was however only 1·57 at 4430 m at Gara Glacier Base Camp.

Contrary to expectation the atmospheric turbidity was high at the Silver Hut Glacier. The amount of precipitable water was also very low. The mean value of the direct solar radiation measured in 1961 was 1·53 cal/cm^2/min at an average absolute airmass of 0·68 and the maximum value 1·65 at an airmass of 0·54. The values show the effect of higher turbidity compared to that at Mount Whitney.

Even at Mauna Loa (3380 m) which is above the normal haze and dust layer and is far from the effects of man made pollution, there was a steady fall in the intensity of the direct solar radiation from 1·75 cal/cm^2/min in 1959 to 1·68 in 1962.

Drummond and Angström (1967) have given the maximum value of direct solar radiation intensity to be observed in the case of no extinction from selective absorption or scattering within the troposphere. As the USSR high altitude balloon measurements show these are reached only above heights of 12 km (Kondrateyev *et al.* 1967).

3·2. *Atmospheric turbidity*

The most interesting conclusion that is evident from Table 11 is that all north Indian stations irrespective of their altitude have a highly turbid atmosphere, even in the high Himalayas. The dust that extends over a large part of north India and extends both to the east and west along the subtropics is a more or less permanent feature of these latitudes.

This was also observed at Sinhagad 305 m above Poona. Poona which was visible till noon on 18 March 1969 from Sinhagad was covered completely by a dense haze layer by afternoon.

Price and Pales (1964) from their nucleus counts at Mauna Loa and Hilo concluded that the afternoon counts at Mauna Loa tend to increase with the influx of more turbid air from lower elevations in the afternoon.

The lowest atmospheric turbidities are observed at Kodaikanal, followed by Shillong and Al Pathar; Gulmarg and Khilanmarg have turbidities which are higher. The high turbidity values as high as 0·045-0·050 imply that 0·12 calories, with the sun in the zenith, are scattered by solid and liquid particles, within the atmosphere above the station. At Mauna Loa where the turbidity is much smaller 0·010 to 0·020 only 0·04 is scattered by the aerosol for vertical incidence of solar radiation. But even here the short term variations are large, about 6 to 7 per cent for airmass 2 and 8 per cent for airmass 3, due to the combined effect of atmospheric turbidity and water vapour absorption and particularly the introduction of more humid air from below.

The values of turbidity and absorption are very consistent and practically independent of the wavelength interval considered, indicating that α is roughly 1·3 and the size of the particles is the same as that for high altitude stations.

As was rightly pointed out by Bishop *et al.* (1966) the comparatively high turbidity over the Everest region is about the same as at Poona for the same period of the year and is fundamentally different from that over Mauna Loa and Mount Whitney. But Bishop *et al.* (1966) assumed the higher particle content to the location in a high altitude valley instead of a free summit. They suggested that the Himalayas protect India from the dusty desert regions of the north.

3.3. *Atmospheric transmission of direct solar radiation*

The transmisivity of the atmosphere for the various stations is tabulated in Tables 1 to 10 and summarized in Table 11. The conclusions are the same as those arrived at as a result of the study of turbidity, high transparency of the atmosphere over Kodaikanal and low transparency in the north Indian stations in the summer months. Nun Kun measurements also showed very low transparency. Only at a height of 4720 m did the transparency exceed 70 per cent. Transparency over Gara Glacier was, however, generally of the ord of 70 per cent and above probably because the wash out of dust by the rains during the monsoon.

4. Conclusion

Measurements of direct solar radiation at a number of high altitude stations in India show that maximum values of the order 1·60 cal/cm²/min at an airmass of 0·88 are received at Kodaikanal (2340 m) while at higher stations in Kashmir and in the Himalayas the values are of the same order even at altitudes of 5710 m a.s.l. The low values of solar radiation are associated with high values of atmospheric turbidity and arise from extinction of the direct solar radiation by aerosols even at these altitudes.

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