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Diagnosis of cloud amount increase from an analogue model of a warming world

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RESUMEN

Son revisados los diagnósticos de las tendencias de la cantidad total de nubes mediante un modelo análogo de "Calentamiento Mundial". Utilizando archivos de datos para la parte continental de los Estados Unidos (publicados), Canada, incluyendo parte del Artico (en preparación), Europa (publicados) y el subcontinente indú (resultados nuevos), se han analizado cambios en la nubosidad en el contexto del modelo análogo que compara registros para dos periodos contrastantes de 20 años. Se encuentra que la cantidad de nubes aumenta sobre prácticamente todo Estados Unidos, Canada, el subcontinente indú y partes de Europa. Durante todas las estaciones estos resultados han sido derivados para una amplia gama de climas y refuerzan considerablemente los hallazgos más tentativos de Henderson-Sellers (1986a, b) y McGuffie y Henderson-Sellers (1987) de que la cantidad total de nubes crece en un mundo que se torna más caliente. Por otra parte los registros de la cantidad total de nubes a partir de 1900, han sido afectados por cambios en las prácticas de observación y reportes a partir de las diferencias en énfasis de los cursos de observación, así como de las diferentes tendencias en los muestreos temporales. Estos aspectos de los registros, son considerados aquí en detalle. Además debe ser reconocido que el registro histórico, aquí revisado corresponde a la superficie terrestre localizada en el Hemisferio Norte, excluyendo muchas áreas correspondientes a los trópicos y a regiones ecuatoriales. Los resultados obtenidos hasta ahora podrían indicar que el experimento transitorio que está ocurriendo en el mundo real, en el que tanto el CO_2 como la temperatura están aumentando, incluye una retroalimentación negativa sobre la temperatura debido al aumento de la nubosidad. Sin embargo, el hecho de que el área estudiada está restringida, puede significar que la tendencia aparente sea mucho menor que la global. Específicamente los resultados son consistentes con las predicciones numéricas en las que las trayectorias de las tormentas se encuentran corridas hacia el polo en los experimentos de aumento al doble del CO_2. También se podrían reexaminar las predicciones de cambios en la nubosidad hechas por modelos numéricos a la luz de los resultados que aquí han sido descritos.

ABSTRACT

"Warming world" analogue model diagnosis of total cloud amount trends is reviewed. Using cloud amount records for the continental U. S. A. (published), Canada, including parts of the Arctic (in preparation), Europe (published) and the Indian sub-continent (new results), cloudiness changes have been analyzed in the context of the analogue model which compares records of two contrasting twenty year periods. Cloud amount is found to increase over practically the entire U. S. A., Canada, most of the Indian sub-continent, and parts of Europe in all seasons. These results have been derived for a wide range of climates and considerably strengthen the more tentative findings of Henderson-Sellers (1986a,b) and McGuffie and Henderson-Sellers (1987) that total cloud amount increases in a warming world. On the other hand, the record of total cloud amount since the 1900s has suffered from changes in observing and reporting practice from differing emphasis on observer training and from time sampling biases. These aspects of the record are considered here in detail. Moreover it must be recognized that the historical record reviewed here is land-based only, contained within the northern hemisphere and excludes many areas especially the tropics and equatorial regions. The results achieved so far could indicate that the current real-world transient experiment in which CO_2 and temperatures are increasing includes a negative feedback on increasing temperatures due to increasing cloud amount. However the very restricted area considered also means that the apparent trend may be much less than global. Specifically results are not inconsistent with numerical model predictions of storm tracks shifted poleward in doubled CO_2 experiments. At the least, the predictions of cloud changes made by numerical models could be re-examined in the light of the results described here.

1. Clouds in a warming world

It is widely accepted that the increase in the concentration of atmospheric carbon dioxide and other trace gases over pre-industrial levels caused by the combustion of fossil fuels and other human activities will lead to increased temperatures (Slocum, 1955; NAS, 1982; WMO, 1986; Dickinson and Cicerone, 1986). Two methods can be employed in attempting to predict the nature of the response of the climate system. One method is the use of general circulation climate models. The other is the study of past climates. In this paper we review one type of analogue model based upon historical records of climatological parameters.

To date all published GCM experiments have considered a change in the equilibrium state of the climate. The basis of the historical analogue investigation of total cloud amount described here is a transient change in climate characteristics. It is not at all clear that transient changes are useful analogues of the differences between equilibrium states. Results suggest that it is certainly insufficient and probably incorrect to infer that a seasonally verified cloud prediction scheme in a GCM will necessarily be appropriate in a warming world situation (Warren and Schneider, 1979 *cf.* Henderson-Sellers, 1986a,b).

Difficulties exist in estimating likely cloud-climate interactions in perturbed climate situations, such as the inability to establish whether an increase in cloudiness, e.g., as a result of increased temperatures and hence increased evaporation, leads to an increase in areal coverage by clouds or to increased vertical extent with possibly even a decrease in areal extent. One of the more difficult climatic feedback processes to measure and hence to model is the cloud-radiation feedback (GARP/JOC, 1978; Wetherald and Manabe, 1980; Ramanathan *et al.*, 1983). The semi-transparent nature of cirrus cloud and the dynamic nature of overlap of layered clouds makes even simplified studies of cloud-climate interactions difficult (Stephens and Webster, 1979; Charlock, 1982; Webster and Stephens, 1984).

GCM studies (e.g., Hansen *et al.*, 1984; Wetherald and Manabe, 1986) have shown an overall tendency for total cloud amount to decrease although this slight decrease is composed of a decrease in low and middle-level cloud particularly in the convectively active regions, such as the tropical and mid-latitude rain belts, in high cloud amount in almost all latitudes. There are also differences in the latitudinal response of cloud cover to increased carbon dioxide as well as more subtle possibilities for changes to the optical properties of the clouds which may imply negative cloud feedback (e.g., Roeckner *et al.*, 1987).

Efforts are now being made to improve the cloud observational data base (e.g., Stowe, 1984; Rossow *et al.*, 1985) but projects such as the International Satellite Cloud Climatology Project (ISCCP), even when successfully completed, will provide only a five to ten year data set. It is unlikely that these satellite based products will be able to furnish adequate information about cloud layering and cloud type, and the differences between satellite and surface based cloud observations preclude, at least at present, any hope of comparing present day satellite retrieved cloudiness estimates with earlier periods of surface based cloudiness observations (Malberg, 1973; Hughes, 1984; Warren *et al.*, 1985).

Surface derived cloud data are predominantly continental and are biased towards low-level cloud amount. Numerical models, on the other hand, predict multi-layer clouds using a variety of prediction schemes (Schlesinger and Mitchell, 1985). Despite these inherent differences between modelled and surface-observed cloudiness most numerical modelling groups are quite prepared to display global maps of predicted cloud and compare these with surface observations of cloudiness. For example, Washington and Meehl (1984) compare the NCAR GCM cloud predictions with the cloud data of London (1957), Hansen *et al.* (1983) compare the GISS GCM cloud predictions with surface observations collected together by Berry *et al.* (1973), Potter and Gates (1984) use the predominantly surface-observed cloud archive of Berlyand and Strokina (1980) and Wilson and Mitchell (1986) choose observational data from Meleshko and Wetherald (1981) which is, in fact, a combination of an earlier version, 1974, of Berlyand and Strokina and the Southern Hemisphere data of Van Loon *et al.* (1972). Acceptance of the verity of surface observed cloudiness information seems to be widespread. It is, after all, at least as easy to retrieve sophisticated and fairly accurate cloud information as to measure accurately most other meteorological parameters. The observer's eye-brain analysis is closer to the clouds than any satellite radiometer and still more sensitive to texture and pattern than computer-based retrieval algorithms.

The historical cloud data collected so far do not permit analysis of anything other than total cloud amount. Even so, the climate modelling community should be encouraged to try to simulate these, and other, observational trends as well as concentrating upon compatibility between satellite-retrieved radiances and cloudiness.

An alternative method of estimating the probable impact of a carbon dioxide induced warming is that of the construction of warm-world analogues from historical meteorological records (e.g., Flohn, 1977; Wigley *et al.*, 1980; Kellogg and Schware, 1981; Lough *et al.*, 1983). Over a decade ago total cloud amount changes in the tropical belt, 25°S to 25°N, were linked to the Southern Oscillation Index and El Niño (Murakami, 1975). Studies, such as the one described here, might be taken as being indicative of changes and conditions to be anticipated during the early phase of CO_2-induced warming, and not necessarily of those of later stages when the gradual, but steady, rise in atmospheric CO_2 levels will cause the climate system to respond relatively slowly. The method used here involves the extraction of a block of warm and a block of cold years from the instrumental record and may, fortuitously, incorporate important changes in oceanic and cryospheric boundary conditions .

2. The historical analogue technique

Fig. 1 shows the location of the 236 stations and (inset) scatter graphs illustrating the wide range of cloud climatological regimes encompassed by this and earlier studies. There are strongly seasonal regimes (e.g., Dwarka and Salt Lake City), generally cloudy locations (e.g., Aberdeen) and areas of relatively little cloud (e.g., Port Said).

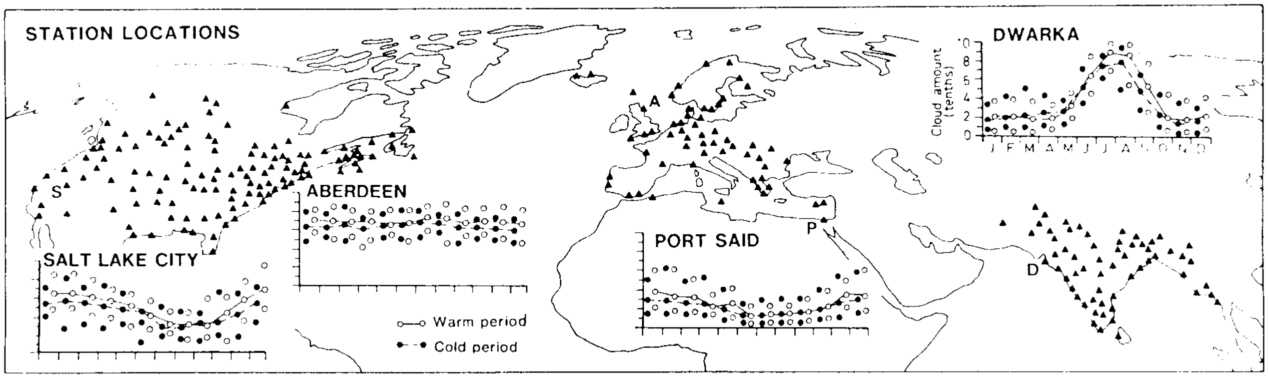

Fig. 1. Map showing location of 236 stations used and example scatter graphs illustrating the range of climatological regimes encompassed.

The analogue technique must be used carefully. There can be no attempt to associate cause and effect in analogue models. Rather the technique depends crucially upon associations in sets of observed values being representative of physical processes. If this is not the case, the analogue technique must fail. In this study, small (0.5 K) temperature increases are associated with small (0.3 tenths) increases in total cloud amount. This is not an unreasonable result and, in the absence of any sound basis for the parameterization of cloud prediction in numerical climate models (e.g., Schlesinger and Mitchell, 1985), an analogue "prediction" based upon good historical records may be of considerable value.

Flohn (1977) and Kellogg (1977) pioneered the use of analogue models to investigate the likely effects of increasing atmospheric CO_2 and their use has been reviewed by Pittock and Salinger (1982). Data from individual years were composited by Wigley *et al.* (1980), contrasting a group of warm years with a group of cold years. More recently Lough *et al.* (1983) have suggested an improvement on this basic technique. They selected the warmest and coldest twenty-year periods from the gridded Northern Hemisphere temperature data produced by Jones *et al.* (1982). Only the temperature data for the period 1901-1980 inclusive were considered. In this period the warmest 20-year period is from 1934-1953 and the coldest from 1901-1920. This analogue method was used successfully by Henderson-Sellers (1986a,b) to examine the probable cloud variation associated with increasing temperatures in Europe and the U.S.A. and this analogue study has been extended here to encompass a much larger area and a wide range of climatological regimes.

Lough *et al.* (1983) comment that comparison of these two periods as an analogue of a warming world has some significant advantages over the method of compositing groups of warmest and coldest years in that any changes in climatic parameters noted in going from the cold to the warm period are likely to be associated with the gradual warming from 1901 to 1983 and may be associated with the increase in atmospheric CO_2 during the early part of the twentieth century. Even if this gradual warming is not the result of increasing atmospheric CO_2, the analogue of slowly changing boundary and temperature conditions is a useful tool with which to study the transient CO_2-induced changes predicted for the present and near future (Wigley and Schlesinger, 1985; Hansen *et al.*, 1985).

In this study we shall consider only the effect on regional cloud amounts of the transient increase in Northern Hemisphere temperature between 1900 and 1954. This method of analysis has the disadvantage of including, as an apparent signal, any trends in observing method. These changes are considered in Section 4 and their impact assessed. We believe that the advantage of considering cloud amount changes in a warming world outweighs this potential disadvantage. Another approach is to compare the warmest five (or ten) years' cloud amounts with the amounts for the coldest five (or ten) years. However, as Fig. 2 indicates, the result of such a study would be very similar to the results we obtain. Fig. 2 compares the Northern Hemisphere temperature data, in the form of anomalies from a 1946-1960 reference period (Fig. 2(a)) with the annual total cloud amount for the four regions derived by averaging observed values from the 236 stations (Figs. 2(b), (c), (d) and (e)). There is a tendency for cloud amount to increase generally over the period of study; although this trend is weak in some areas (especially Europe) and somewhat out of phase (compare U. S. A., Fig. 2(c) with India, Fig. 2(d)). Figs. 2(c) and 2(e) have been extended beyond the period of study here. The upward trend in total cloud amount seems to continue, for the stations in the continental U. S. A. and Canada at least, to date, overcoming the slight decrease in the early 1950s.

Notwithstanding the suggestion in Fig. 2 of an upward trend in the total cloud amount over the period when temperatures increased, caution must be exercised when applying the historical

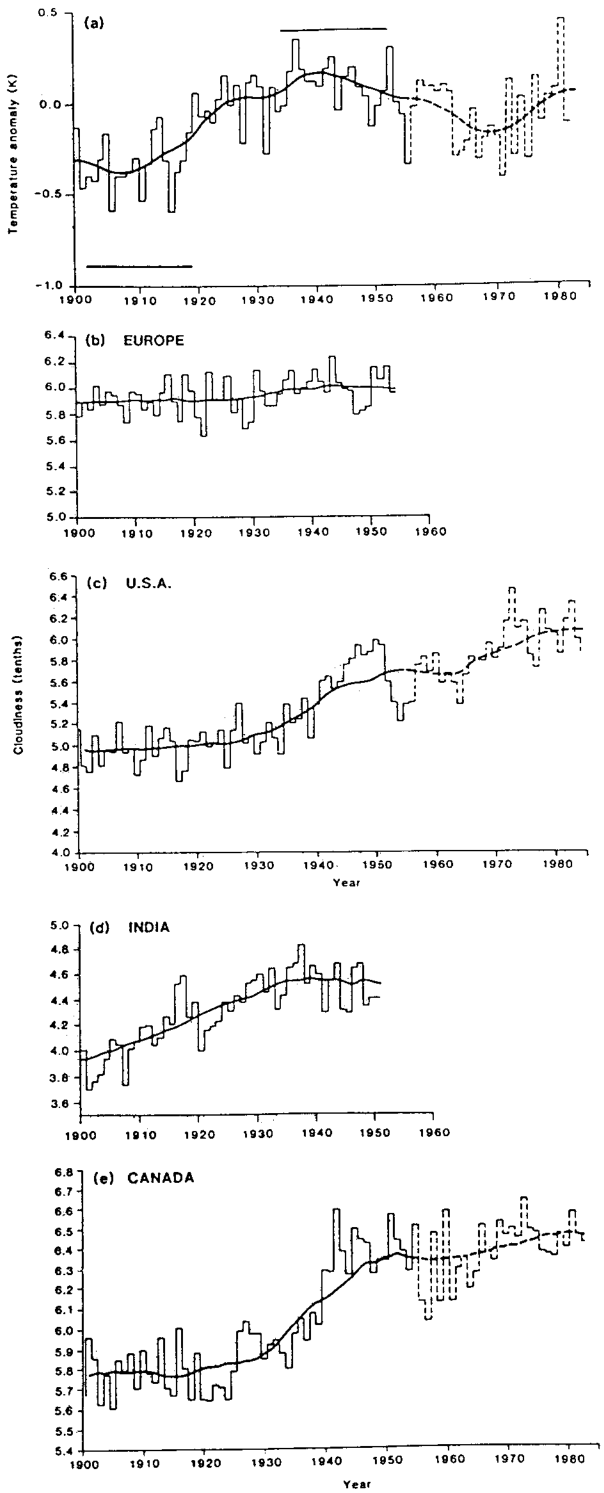

Fig. 2. (a) Northern Hemisphere mean surface air temperature variations (K) since 1900 shown as anomalies from 1946-1960 reference period. The curve is of 20 year filtered values. Data and filtered values more recent than 1954 (the end of this evaluation) are dashed. The warm and cold periods used here are marked (redrawn from Lough *et al.*, 1983). (b) European mean annual cloud amount, 58 station average for the period 1900-1954. (c) U. S. A. mean annual cloud amount, 77 station average for the period 1900-1954. Dashed values are shown from 1955 to 1984. (d) Indian sub-continent mean annual cloud, 60 station average for period 1900-1954. (e) Canadian mean annual cloud, 41 station average for period 1900-1954. Dashed values are shown from 1955 to 1982. In each case (b)-(e), the smooth curve is of 20 year filtered values.

analogue method and in particular when considering the topic of cloud changes. Hemispheric mean temperatures fell by ~0.3°C in the 30 years (1945-1975) when atmospheric CO_2 concentrations were increasing most rapidly and this suggests that factors other than CO_2, or combining with CO_2, have at least a comparable effect on temperature. Recent estimates of the increase in global mean temperature caused by changes in CO_2 concentration over the last century (Wigley and Schlesinger, 1985), allowing for oceanic thermal inertia, range between 0.3 and 0.8°C. Thus the contribution of increased CO_2 to the observed warming between the two twenty year periods used here is likely to be ~ 0.2°C suggesting that, at most, only approximately half the observed warming of 0.4°C can be attributed to CO_2. There is no guarantee that the other factors contributing to the observed warming, for example long term but, perhaps, eventually random fluctuations in ocean temperature (Folland *et al.*, 1984; Jones *et al.*, 1986) would produce the same changes in cloudiness found with increased CO_2. Despite these caveats this investigation of cloud amounts offers a possible link between increasing atmospheric CO_2 and cloudiness which is an alternative to numerical modelling results. The cloud data described here also offer a means of examining the predictions of numerical climate models which should be exploited. At the very least the record of total cloud amount described here is worthy of careful examination.

3. Historical cloud data

The vast majority of the cloudiness data described here have already been discussed in earlier publications (Henderson-Sellers, 1986a,b; McGuffie and Henderson-Sellers, 1987) and are therefore reviewed only briefly here. The most recently acquired data from the Canadian Arctic (Henderson-Sellers and McGuffie, 1989) and from the Indian sub-continent (unpublished) are discussed in more detail.

Cloud data for Europe were derived from 58 stations covering a wide geographical area. Because of the volatile political history of Europe meteorological data are collected into many different series of archive volumes: 43 different sources were consulted in all (see Henderson-Sellers, 1986a). Unlike the situation in Europe, where observations of a meteorological nature had often been made since the seventeenth century and were commonplace by the early 1900s at many national (often astronomical) observatories, climatic data for the early part of this century are somewhat sparse in the United States.

The most satisfactory source of archive material for the continental United States was found to be the Climatological Record Book. From here 77 stations were selected from which temporally continuous data were available (Henderson-Sellers, 1986b). These records were much more consistent in method and in number of observations made per day than were the European cloud observations.

The situation in the United States has been examined by Changnon (1981) with specific reference to the possible influence of jet contrails. Angell *et al.* (1984) also considered cloud and sunshine data between 1950 and 1982 and found a significant increase in cloudiness over much of the United States. Analysis of the cloud data for Europe suggested that cloud cover had generally increased in moving from the cold period (1901-1920) to the warm period (1934-1953). However an area of decrease existed over the central part of the area considered (Germany, France and some parts of Spain) . The results of Henderson-Sellers (1986a) are in part consistent with an increase in the frequency of anticyclonic blocking situations in Europe in the warm period. In the study of Henderson-Sellers (1986b) cloud amount increases were found to be much more consistent and extensive over the continental United States, a pattern consistent with the observed general reduction in mean sea level pressure over that area. This result is in agreement with the report by Seaver and Lee (1987) that the number of cloudless days over the United States shows a statistically significant decrease between the early and latter parts of this century. The positive nature of these two regional studies has prompted this more geographically extensive data retrieval exercise which encompasses the Indian sub-continent and Canada including the Canadian Arctic.

Sixty stations were selected from the area of the Indian sub-continent. Sources of the cloud data were the Indian Weather Review, The Meteorology of Ceylon and Results of Meteorological Observations in Ceylon and the Climatological Summary of Burma (Table 1 and see McGuffie and Henderson-Sellers, 1987).

Many stations reported in the Indian Weather Review, have a gap in the data record from 1949 to 1953 inclusive, with the observations beginning again in 1954. Stations in Burma are without data after 1941 due to the disruption by the Japanese occupation. In general any gaps in the record affect nearly all the stations simultaneously but these are rarely extensive.

In India there was generally only one observation made per day, until about 1933, usually at around 8 a.m. local time although some station reports include more than one observation in the monthly mean reports. From 1933 to 1954 there were, usually, 2 observations per day, typically at 8 a.m. and 4 p.m. local time although the times differ. The observations seem to have been made in tenths of sky cover throughout the period and monthly means are in tenths.

Canadian meteorological reports date back to the 1850s (*cf.* Hamilton, 1986). The source of all the Canadian data used here is the Monthly Record of Meteorological Observations for Canada issued annually. Originally produced in 1873 by the Department of Marine and Fisheries and termed the "Canadian Meteorological Service Report", it was renamed in 1916 and became the responsibility of the Canadian Meteorological Service. The report retained its annual and national format until 1977, when reporting stations were divided geographically so that six reports were issued each year for western, eastern and northern Canada for the two half years January/June and July/December.

Fifty one stations were selected altogether but 7 of these (the Arctic stations) do not have observations before ~1930 and another 3 begin observing only in 1916 (i.e., there are only 41 throughout most of the study period) . This data set is currently being expanded to include the Canadian Arctic (Henderson-Sellers and McGuffie, 1989). The stations selected (see Table 2) are almost all Class II observing stations and, although it would have been possible to replace some of the selected stations with adjacent Class I (the most complete reports) stations for part of the record, it was deemed more appropriate to retain consistency throughout .

In Canada cloud observations have been made in tenths throughout but recording was in either tenths or percentages. Times of observations vary through the study period, and generally the number of observations made during each 24-hour period increases through the century, although even in 1900 about half the stations made three observations per day (usually at 8 or 9 a.m., 3 or 4 p.m. and 8 or 9 p.m.), the other having two reports. By the 1950s there are often 4 or 5 observations. There is some confusion in the earlier records concerning the time of the observations. Often the record states that observing times are 75th meridian times rather than local times but this is not always the case. Between 1900 and 1916, times appear to be 75th meridian times and after 1916 three or more time bases, including local time, are used.

Table 1. Location and barometer height of Indian sub-continent stations

Station	*Location* (N, E)	*Height* (m)
Rawalapindi	33°40', 73°08'	511
Lahore	31°33', 74°20'	214
Chaman	30°55', 66°27'	1314
Jacobabad	28°18', 68°28'	56
Bikaner	28°00', 73°18'	224
Jodhpur	26°18', 73°01'	224
Kota	25°09', 75°51'	274
Ahmadabad	23°04', 72° 38'	55
Indore	22°43', 75°48'	567
Dwarka	22°22', 69°05'	11
Surat	21°12', 72°50'	12
Bombay	19°07', 72°50'	4
Ratnagiri	16°59', 73°20'	69
Karwar	14°47', 74°08'	4
Mangalore	12°52', 74°51'	22
Ootacamund	11°24', 76°44'	2249
Trivandrum	08°29', 76°57'	64
Columbo	06°54', 79°52'	7
Madurai	09°57', 78°07'	133
Madras	13°04', 80°15'	6
Bangalore	12°58', 77°35'	921
Nagappattinam	10°46', 79°51'	9
Kadaikanai	10°14', 77°28'	2343
Nellore	14°27', 79°59'	20
Raichur	16°12', 77°21'	400
Nizamabad	18°40', 78°06'	381
Aurangabad	19°53', 75°20'	581
Balasore	21°31', 86°56'	20
Raipur	21°14', 81°39'	298
Calcutta	22°32', 88°20'	6
Barisal	22°45', 90°22'	4
Ranchi	23°26', 85°24'	652
Patna	25°36', 85°06'	60
Gaya	24°45', 84°87'	116
Mymensingh	24°43', 90°26'	19
Bogra	24°51', 89°22'	-
Dinajpur	25°38', 88°44'	37
Purnea	25°46', 87°28'	38
Gauhati	26°06', 91°35'	54
Darbhanga	26°10', 85°54'	49
Delhi	28°34', 77°07'	233
Bareilly	28°22', 79°34'	173
Roorkee	29°51', 77°53'	274
Kyavkpyu	19°25', 93°33'	5
Rangoon	16°46', 96°10'	15
Tavoy	14°06', 98°13'	17
Bhamo	24°16', 97°12'	113
Monywa	22°06', 95°08'	82
Cawnpore	26°26', 80°22'	126
Silchar	24°49', 92°48'	29
Sibsager	26°59', 94°38'	97
Yamethin	20°25', 96°09'	199
Moulmein	16°30', 97°37'	22
Nagpur	21°06', 79°03'	310
Akola	20°42', 77°02'	282
Multan	29°58', 73°15'	123
Satna	24°34', 80°50'	317
Chitaladroog	14°14', 76°26'	733
Gopalpur	19°16', 84°53'	17
Diamond Island	15°15', 97°52'	7

Notes

1. Spelling of place names are taken from the archive records and sometimes differ from present day spelling.
2. Temporal coverage is consistently good until the early 1950s.

Table 2. Location and barometer height of Canadian stations

Station	*Location* (N, W)	*Height*
British Columbia		
Kamloops	50°41′, 120°29′	398
Prince Rupert	54°18′, 130°18′	57
Vancouver	49°17′, 123°5′	45
Victoria	48°24′, 123°19′	28
Yukon		
Dawson	64°4′, 139°20′	351
North West Territories		
Hay River	60°51′, 115°20′	176
Alberta		
Calgary	51°2′, 114°2′	1130
Edmonton	53°33′, 113°30′	719
Fort Chipewyan	58°42′, 110°10′	238
Medicine Hat	50°5′, 110°37′	720
Saskatchewan		
Battleford	52°41′, 108°20′	540
Prince Albert	53°10′, 106°0′	447
Swift Current	50°20′, 107°45′	813
Manitoba		
Churchill	58°45′, 94°07′	38
Minnedosa	50°15′, 99°50′	566
Norway House	53°58′, 97°52′	240
Winnipeg	49°53′, 97°7′	253
Ontario		
Kapuskasing	49°25′, 82°26′	310
London	42°59′, 81°13′	269
Ottawa	45°26′, 75°42′	98
Parry Sound	45°19′, 80°0′	212
Port Arthur	48°27′, 89°12′	215
Southampton	44°30′, 81°21′	219
Toronto	43°40′, 79°24′	117
White River	48°35′, 85°16′	417
Québec		
Anticosti	49°24′, 63°35′	10
Father Point	48°31′, 68°19′	7
Harrington Harbour	50°40′, 59°19′	8
Montréal	45°30′, 73°35′	62
Québec	46°48′, 71°13′	99
New Brunswick		
Chatham	47°3′, 65°29′	7
Fredericton	45°57′, 66°36′	55
St. John	45°17′, 66°4′	23
Nova Scotia		
Halifax	44°39′, 66°36′	32
Sable Island	43°57′, 60°6′	8
Sydney	46°10′, 60°10′	12
Yarmouth	43°50′, 66°2′	22
Prince Edward Island		
Charlottetown	46°14′, 63°10′	13
Newfoundland		
Belle Isle	51°53′, 55°22′	145
St. George's	48°27′, 58°30′	7
St. John's	47°34′, 52°42′	42

Notes

1. Years 1900-1904 of Vancouver, British Columbia, are taken from the adjacent station (new Westminster, 49°13′N, 122°54′W) which Vancouver seemed to replace in 1905.
2. There is some confusion about the precise location of the station at Medicine Hat, Alberta; the longitude is given as 111°37′ on a number of occasions. The station seems to have been moved from 50°1′N to 50°5′N in 1916.
3. Battleford, Saskatchewan, was originally named North Battleford. The location does not seem to have changed.
4. Years 1900-1920 for Churchill, Manitoba, are from Fort Churchill at the same location.
5. Rivers (50°02′N, 100°14′W) replaces Minnedosa, Manitoba after 1949.
6. Years 1910-1939 for Kapuskasing, Ontario, are from Cochrane (49°2′N, 81°0′W).
7. From 1941 onwards Port Arthur, Ontario, has been replaced by data from Fort William at the same location.
8. Harrington Harbour, Québec, moved from 50°30′N, 59°29′W to its present location in 1912.
9. St. George's, Newfoundland, moved from 48°40′N, 58°27′W to its present location in 1911.

As with the previous studies all the available data have been averaged into a monthly mean value of total cloud amount. Thus these ambiguities at individual stations in the actual observing time are of no real significance to the monthly mean values of total cloud amount analyzed here although the timing and number of observations may well bias the record as discussed in Section 4. Typographical errors are rather common in the bound volumes. It is fairly easy to identify errors in transcription of the station location but the stated barometer height also varies at many stations by larger amounts than seems likely as a result of minor station/instrument relocation. These errors suggest that there may also be errors in the transcription of observations. In general it is impossible to identify such errors although some station/year cloud amounts do seem to have been given in tenths even though the table heading states the values are percentages. When these errors were quite clear (for example, Prince Albert, Saskatchewan, being quoted as having a mean January cloud amount of 4.4%) they have been corrected.

The use of surface observer reports of cloud amount requires some assumptions to be made about the accuracy of such observations. It is well established that cloud observations made even by trained meteorologists will differ from individual to individual (e.g., Merritt, 1966) . However there is less discrepancy between estimates of total cloud amount than between different observers' assessment of cloud type and height. It seems unlikely that there should be any systematic bias in the cloud reports so that monthly means and hence the seasonal and annual averages analyzed can be regarded as being fairly representative. Additionally, each station can only be assumed to be representative of its immediate location. Malberg (1973) estimates that surface-based observations are typical of a circular area of radius ~50 km centred at the observing site.

The characteristics of the cloudiness data for the cold and warm periods in India are illustrated in Figs. 3 and 4. Histograms of percentage frequency of occurrence of cloud amount in tenths are shown for both periods in Fig. 5. It should be recognized here that there may be a bias in the Indian record because, as noted previously, most stations made only one report per day until 1933 (i.e., the whole of the "cold" period) switching to two reports thereafter. The implications of such observational biases are discussed in Section 4.

The influences upon the cloud regime of India may be summarized by considering three regions. In the south-east and in Sri Lanka the maritime influence in all seasons (north-east winds in the cool season (DJF), westerly and south-westerly winds in the wet season) means that the cloud follows no strong seasonal pattern (Fig. 6(a)). Further to the north (Fig. 6(b)), the north-easterly winds which

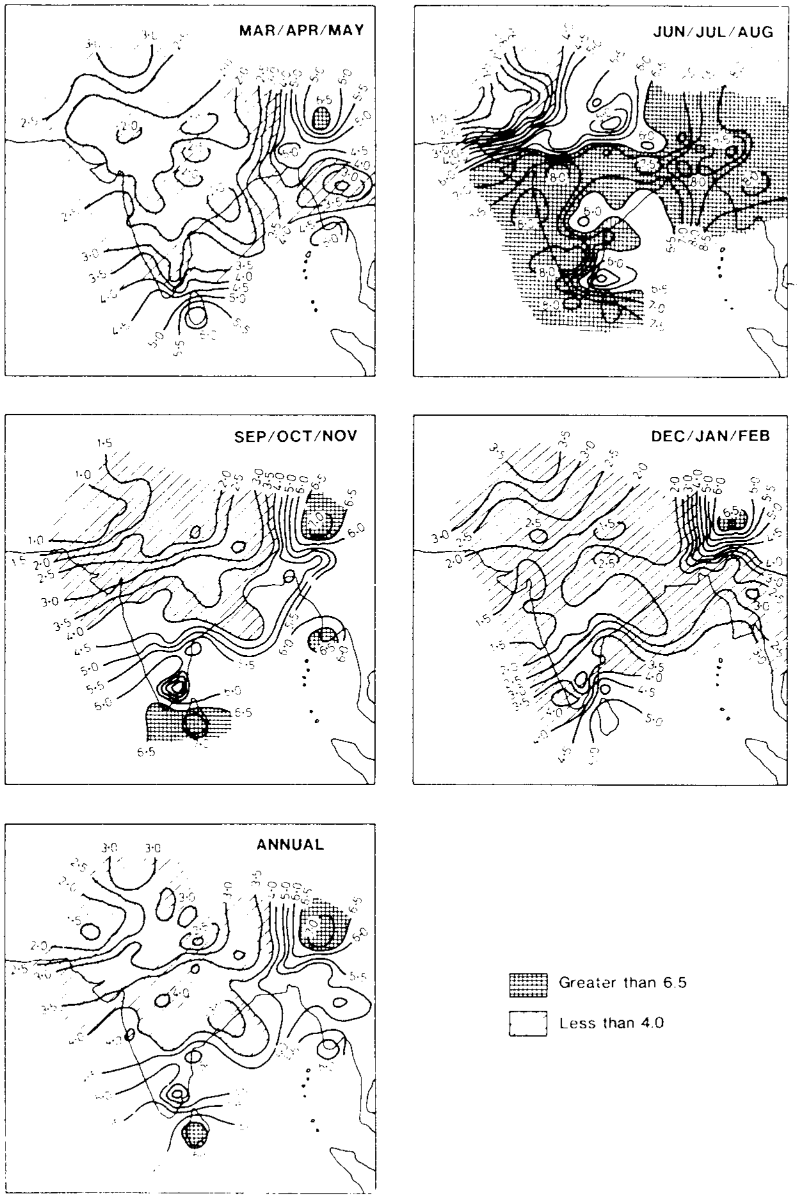

Fig. 3. Indian sub-continent mean total cloud amount in tenths for the cold period for the annual and four seasonal values.

blow in DJF do not cross the ocean and consequently the moisture and cloudiness in the cool season are reduced. This region stretches from the west coast across the northern part of the subcontinent to Bangladesh. The west coast of Burma is influenced by a similar regime. The third region is to the north and west. This region is influenced for most of the year by airflow from the north-west and consequently the lower moisture content of the air results in low values of cloudiness all year (Fig. 6(c)), again with no marked seasonal cycle.

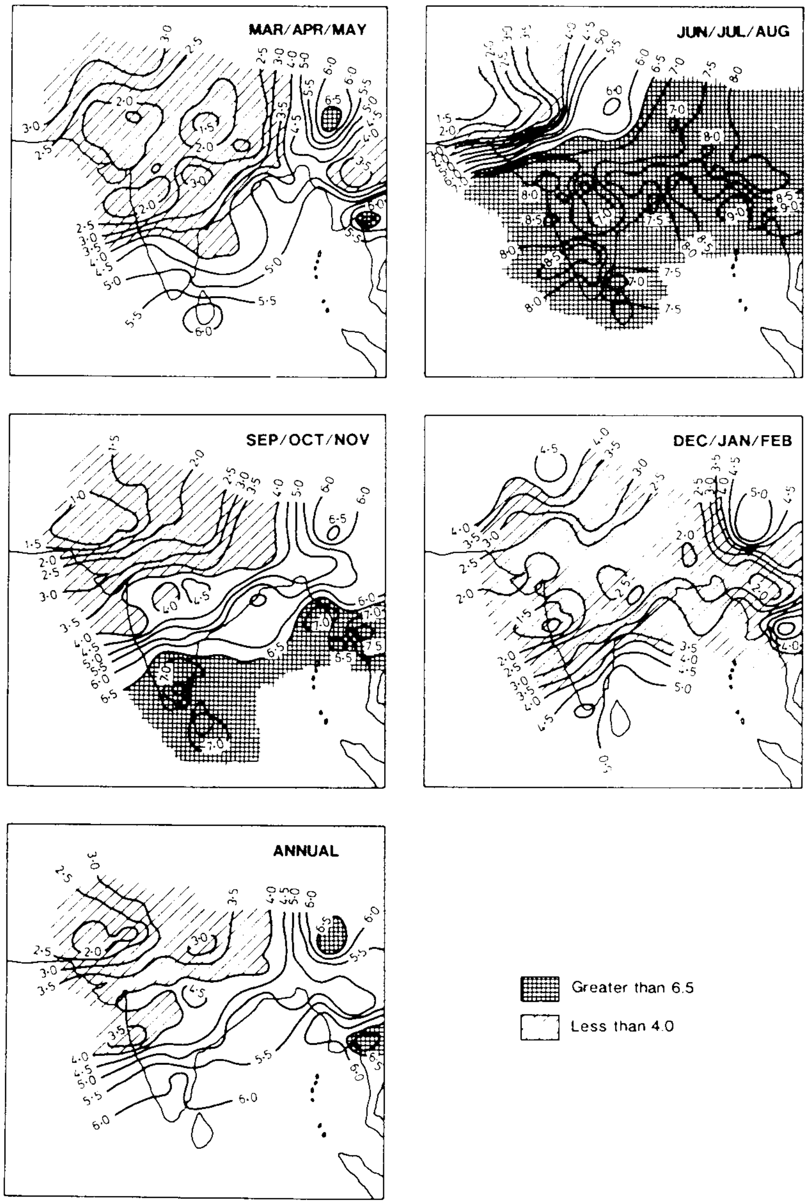

Fig. 4. Indian sub-continent mean total cloud amount in tenths for the warm period for the annual and four seasonal values.

Figs. 7 and 8 illustrate the characteristics of cloudiness over Canada during the warm and cold periods respectively. Frequency distributions for the 41 stations are shown in Fig. 9 for the warm and cold periods. In many cases a change in cloud amount frequency distribution is clear. Fig. 9 also presents an opportunity to examine the features of Canadian cloud climatology. Compared to the dynamic seasonality exhibited in the graphs of Indian cloudiness, the situation over Canada is much less extreme. In general, few areas display a very marked seasonality in cloudiness. Greatest seasonality (Fig. 10) is found in southern Ontario (e.g., London) and on the west coast (e.g., Victoria), with stations situated at the mouth of the St Lawrence generally showing a very low seasonality (e.g., Belle Isle). Further to the north the seasonality begins to increase (e.g., Churchill) but the seasonality typical of Arctic regions is not evident south of the archipelago. Cloudiness is generally greatest on the west coast (e.g., Prince Rupert) but there are no regions where cloudiness is particularly small at any time.

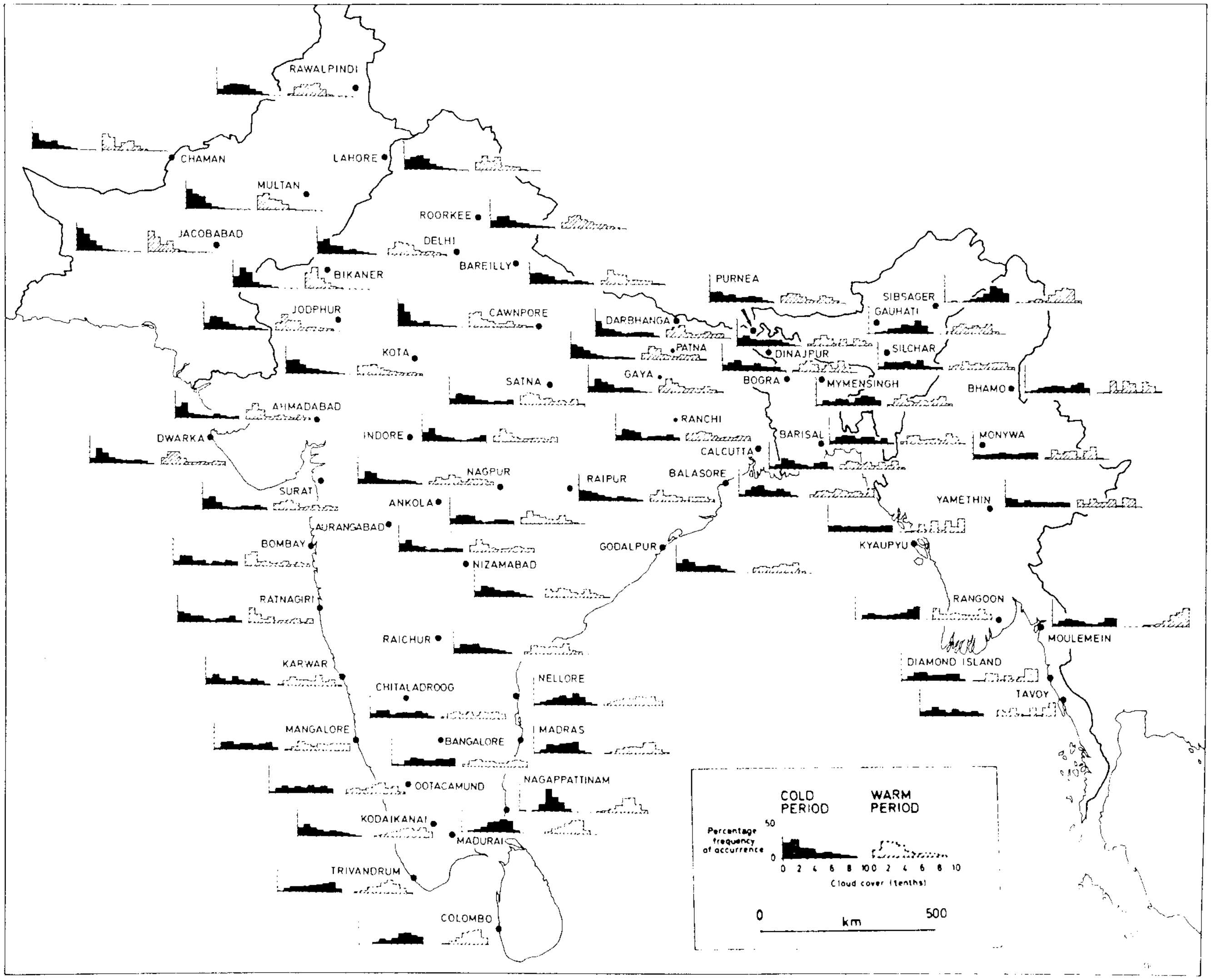

Fig. 5. Location of the 60 Indian sub-continent stations used in this study. The cloud characteristics are illustrated by a pair of histograms of percentage frequency of occurrence of mean monthly cloud amount for the cold and warm periods.

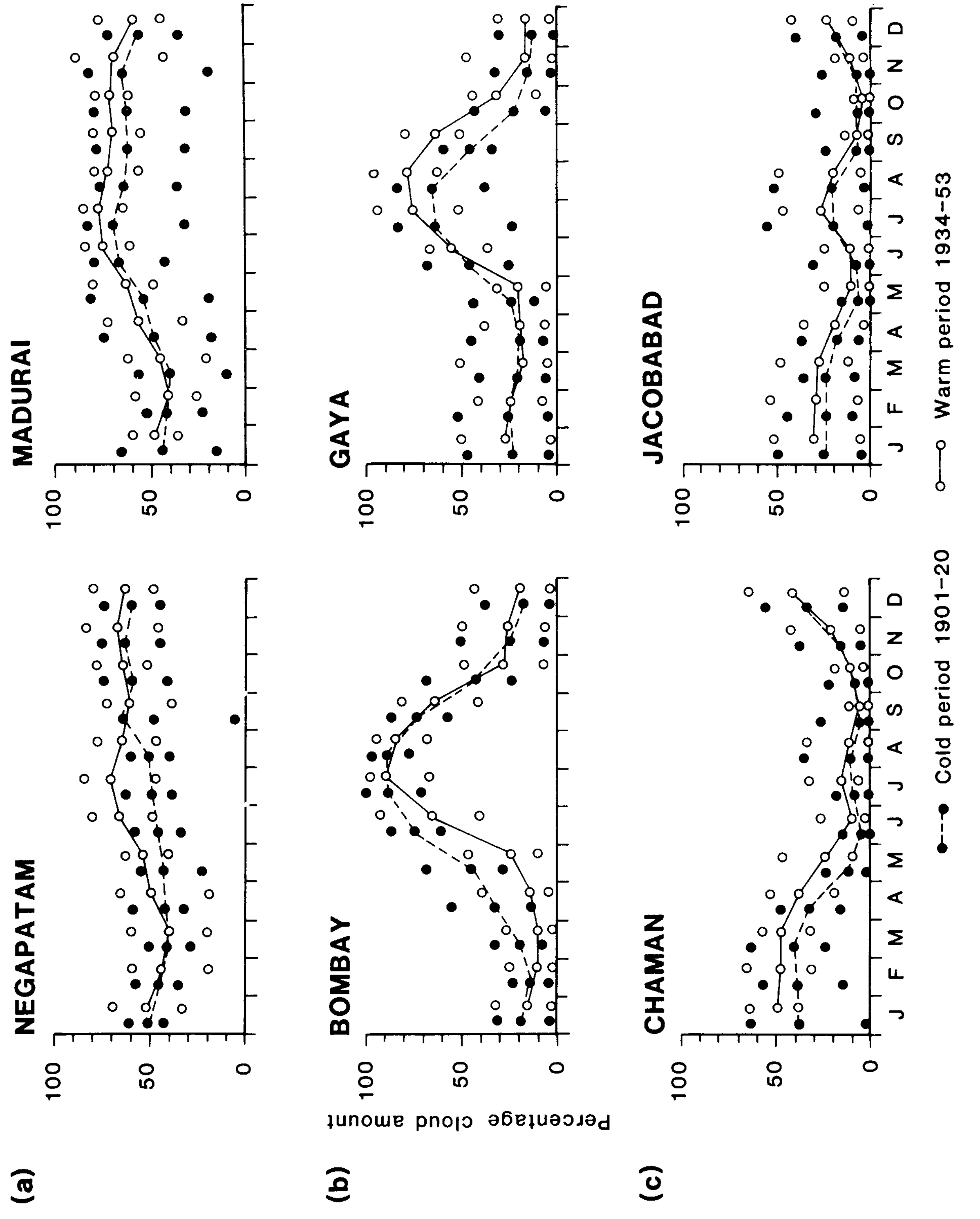

Fig. 6. Scattergraph for selected Indian sub-continent stations: (a) Negapatam and Madurai. (b) Bombay and Gaya. (c) Chaman and Jacobabad

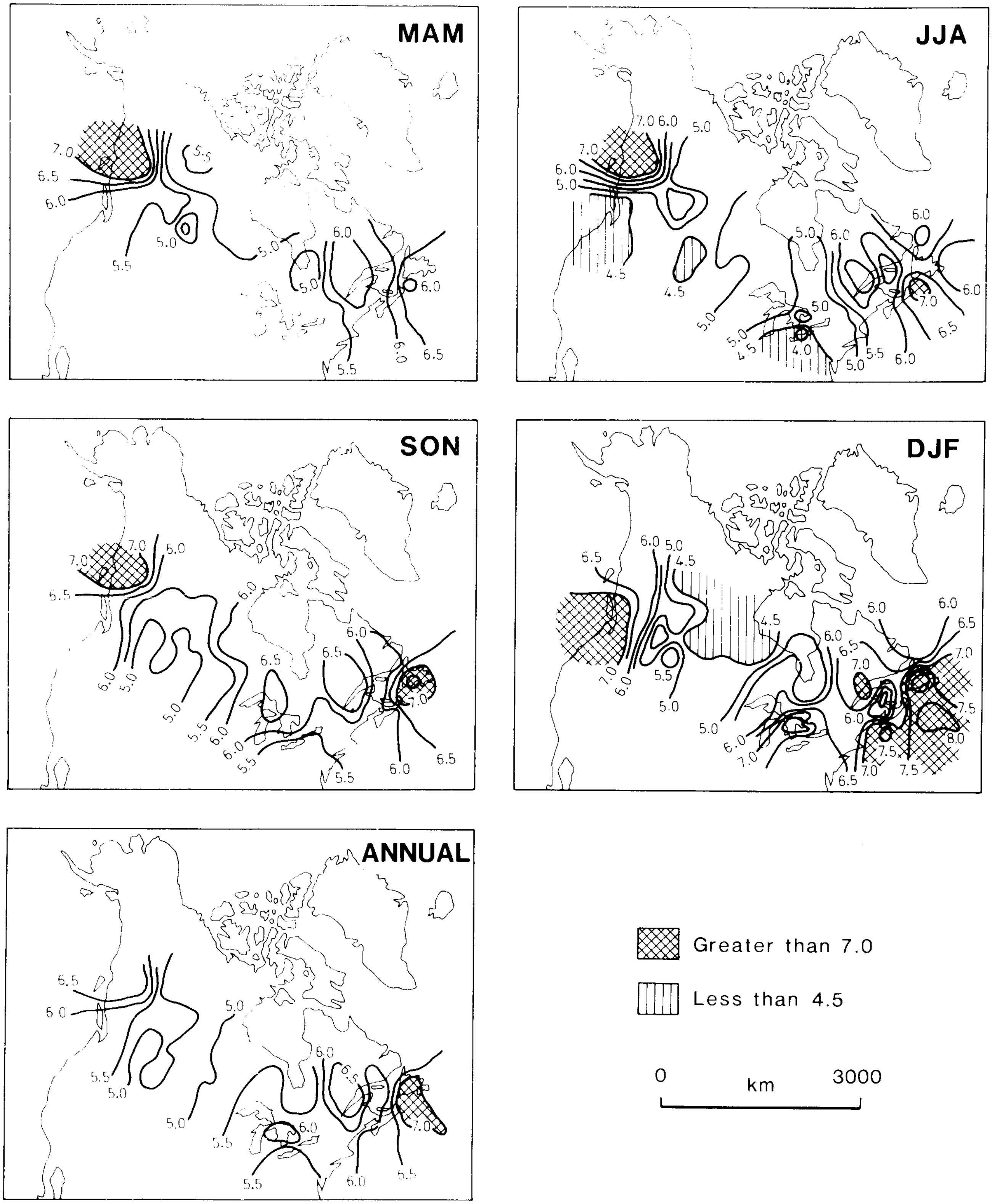

Fig. 7. Canadian mean total cloud amount in tenths for the cold period for the annual and four seasonal values.

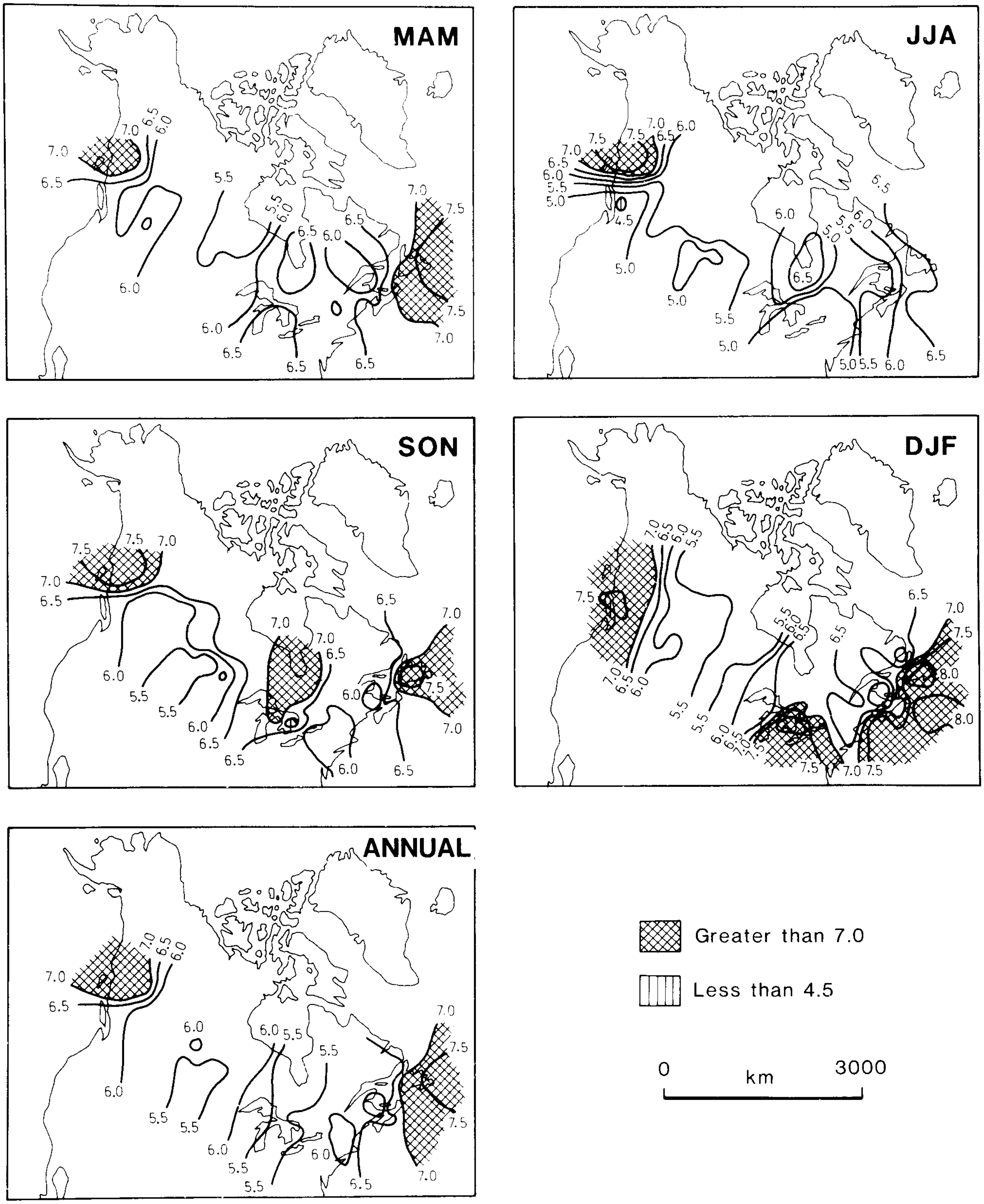

Fig. 8. Canadian mean total cloud amount in tenths for the warm period for the annual and four seasonal values.

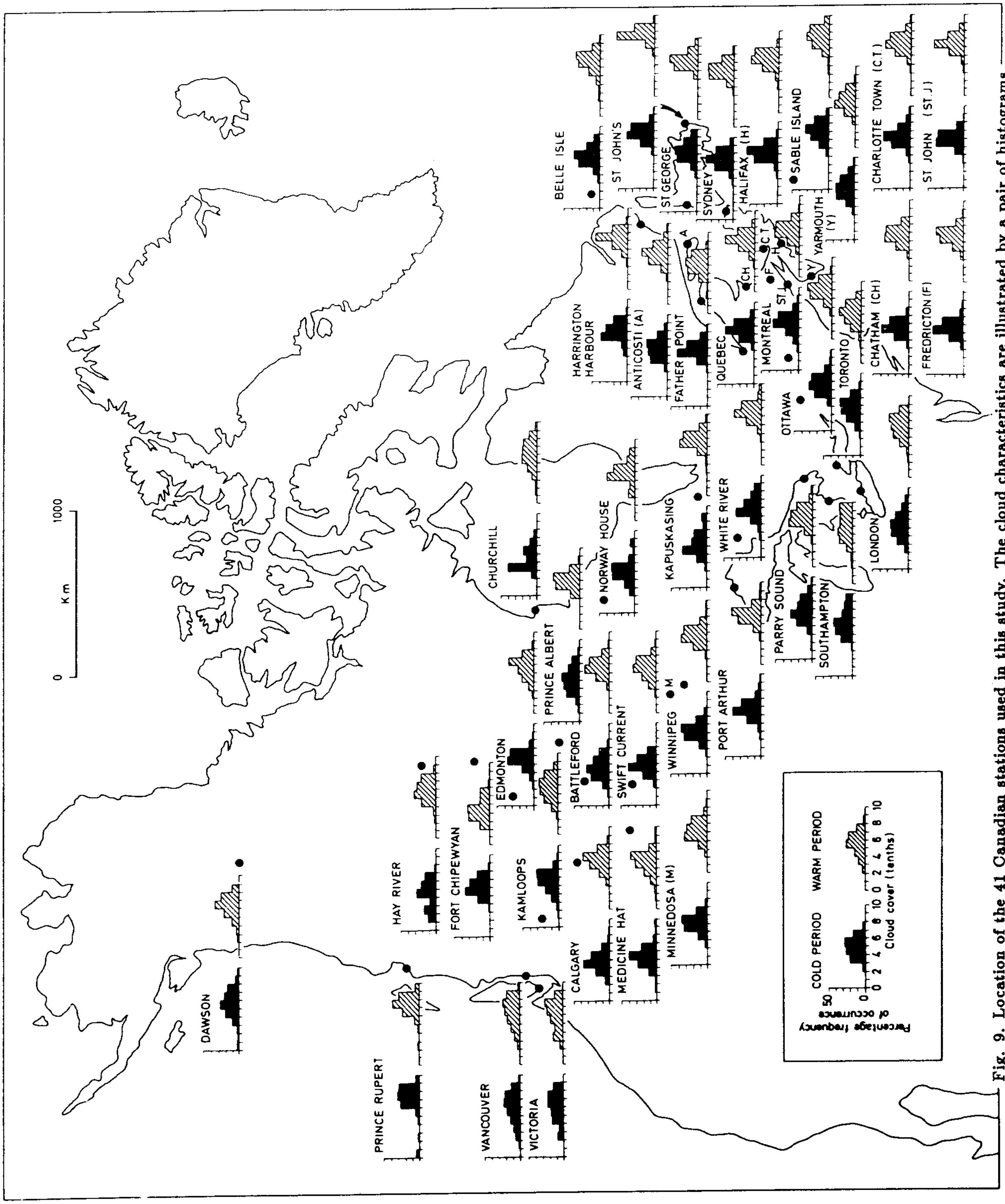

Fig. 9. Location of the 41 Canadian stations used in this study. The cloud characteristics are illustrated by a pair of histograms of percentage frequency of occurrence of mean monthly cloud amount for the cold and warm periods.
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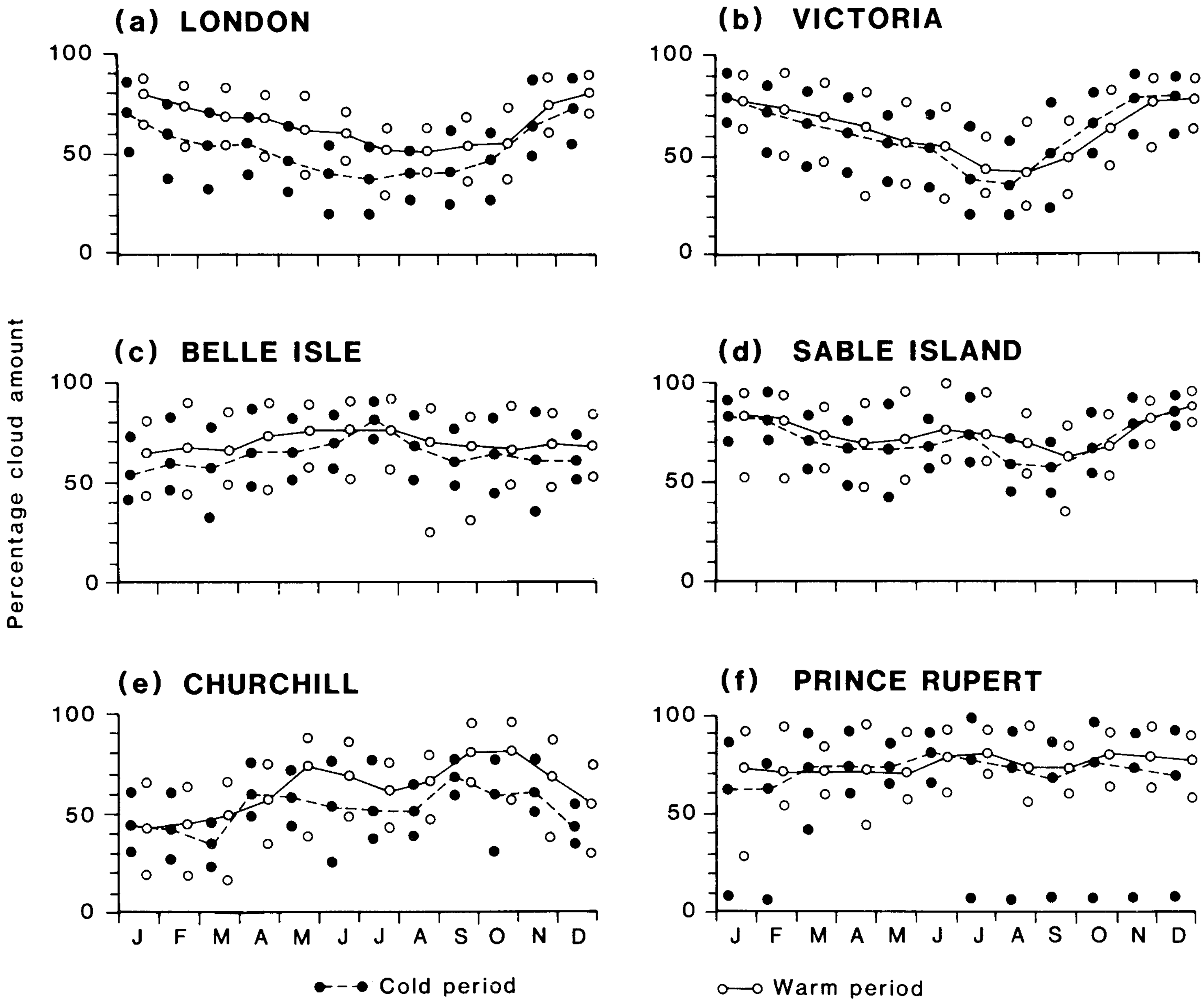


Fig. 10. Scattergraph for selected Canadian stations: (a) London. (b) Victoria. (c) Belle Isle. (d) Sable Island. (e) Churchill. (f)Prince Rupert.

4. Bias a possible errors in historical records of cloud amount

4.1 Temporal sampling

Historical records of cloudiness from 236 stations in 3 continents have been considered in this historical analogue study. The distribution of these stations and example total cloud amounts characteristics are shown in Fig. 1. As is clear from the description of the archive records used, given in Section 3, a number of changes have taken place in the method and number of observations made over the first fifty years of this century. Fig. 11(a)-(c) illustrates some of these changes for three example years: 1900, 1925 and 1951. In each of these maps the station location is shown by a symbol representing the number of observations made per day. Inset on the maps are examples of the timing of different stations' reports illustrated by means of a 24 hour clock face.

The most straightforward case is the Indian sub-continent, for which there was only one observation made per day until 1933 and subsequently (until the early 1950s at least) two observations per day. In North America two observations were generally made from the turn of the century rising to 4 observations per day by the early 1950s. In Europe the situation is very heterogeneous with French stations making 7 reports in 1900, but only 4 by 1925. Other stations make 3 reports throughout the time period although there is a general tendency for the number of reports made per day to increase throughout the century (e.g., Scilly).

It is quite reasonable to suppose that the number of observations made per day and the timing of these observations might have an important influence on the mean monthly cloud amount archived. This would certainly be the case if, for example, there were a strong diurnal variation in cloud amount with, say, the smallest cloud amount occurring near sunrise and the largest in late afternoon. In these circumstances one observation per day, made at 8 or 9 a.m. local time, might be expected to underestimate seriously the daily, and hence the monthly, cloud amount. The Indian sub-continent provides an opportunity to examine this hypothesis since all 60 stations considered returned only one (8 a.m.) cloud amount report until 1933 when 2 (6 a.m. and 4 p.m.) reports were made. It might be anticipated that the total cloud amount curves would exhibit a discontinuity at this time. However, reference to Fig. 2(d) shows that this is not the case. On the contrary, most of the cloud amount increase shown in the smoothed trend occurs prior to 1933 with almost no rise above this value to the early 1950s.

Notwithstanding this result, it does seem worthwhile to consider the possible impact upon archived monthly cloud amounts of the increasing number of reports made in each 24 hour period. It is generally assumed that cloudiness shows a diurnal peak in the mid afternoon. The physical reasoning which is appealed when this assertion is made is that convective activity is likely to peak soon after two or three p.m. local time causing the hypothesised peak in cloudiness at least over continental areas. It is very difficult to examine this hypothesis, since good records with adequate temporal sampling are not available for many areas of the globe. However, some estimates can be made from the very few global cloud archives which exist. One such investigation utilised the U. S. Air Force's 3D Nephanalysis data which is itself a synthesis of conventional and satellite observations of cloud. Using this data base the diurnal signal of mean monthly cloud amount was examined for the four canonical months (January, April, July and October) for the year 1979. Table 3 lists the times of maximum cloud amount for selected areas. In general, it can be seen that 0600 hours occurs slightly more often than the other local times and this was also true for the global analysis.

Whilst these results cannot be said to be representative of the historical cloud data considered here, they do suggest that the simple assertion that cloud amount reaches a maximum some time after midday local time, may not necessarily be correct. This suggestion is also borne out by recent attempts to derive cloud-free images of the Earth's surface. It would be very satisfactory if, by flying a satellite which had an early morning retrieval time, the problem of cloud contamination could be reduced. However, whilst theory suggests that afternoon convection prevails in the tropics, cloudiness is, in truth, a 24 hour per day problem. Use of a morning observation, perhaps similar to

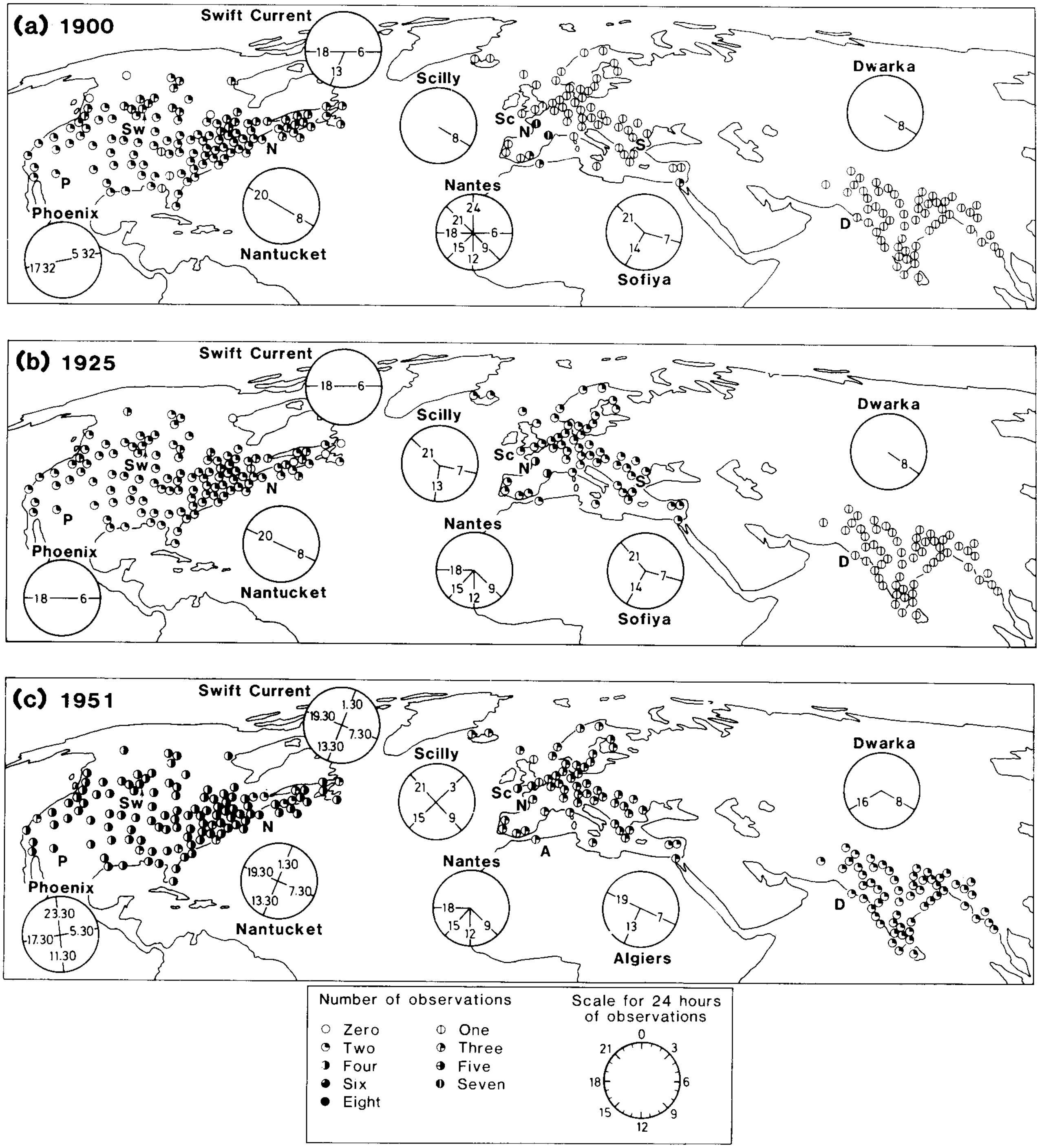


Fig. 11. (a) 1900 cloud reports at each station. The okta is used to show the number of observations made per day and, inset, are examples of typical local times of observation (b) as for (a) but for 1925. (c) as for (a) but for 1951.

that of Landsat, would probably not improve surface retrieval significantly. In more than ten years of mid-morning observation it has not yet been possible to retrieve a single scene over Altamira in Para, Brazil, that has less than 30% cloud cover.

Table 3. Time of maximum cloud amount (LT) for selected areas

	Jan	Apr	Jul	Oct
West coast S. America	06	06	06	06
East coast S. America	06	06/12	12	12
West coast S. Africa	06	-	12	12/18
East coast S. Africa	06	06	12	12
S. Indian Ocean	06	06	12/18	12
Mid Pacific Ocean	-		12/18	12/18
S. America	12	12	-	~06
S. Africa	12	12	-	06
Australia	00	00	-	-

-no obvious time of maximum cloud amount

4.2 Brief history of observing practice

In the 1900s cloud amount seems to have been observed and recorded in tenths of sky cover fairly widely. However, at the Conference of the International Meteorological Organization, held in Washington, D. C. in 1947, it was recommended that amount of cloud be reported in eighths instead of tenths. This change of procedure was brought into force with the introduction of the revised International Code (Washington) on 1 January 1949. This revision in the reporting procedure for cloud amount was adopted by the western world in January 1949. However, most of the eastern bloc countries postponed the adoption of the code until 1950 and the USSR did not implement the revised code until February 1953. Furthermore only some nations changed observing procedure, although all adopted the new reporting practice. Thus, the U. K. observing procedure, as described by Her Majesty's Stationery Office's publications now states that cloud amount estimates shall be made in eighths. It further suggests that it is "convenient to imagine the sky divided into quadrants by two arcs drawn at right angles through the zenith. Each quadrant then represents two eighths of the total sky. If we choose the most appropriate of the figures:

0 = clear or almost clear of cloud

1 = about half-covered

2 = completely or almost completely covered with cloud,

for each separate quadrant and the total amount of cloud for the whole sky is simply obtained by adding the amounts in the separate quadrants". (HMSO, Marine Observers Handbook 10th edition). On the other hand, the U. S. observing procedure continues to use fractional estimates of sky cover made in tenths but the reports made in the international synoptic code are of the fraction of sky covered in oktas (eighths). The conversion is made according to Table 4 so that when no clouds are present okta code figure zero is reported; when any particles of cloud exist up to 1-tenth cloud cover okta code figure 1 should be recorded; when nine tenths of cloud cover, or an overcast with small openings exist, okta code number 7 is reported and when the celestial dome is completely overcast okta code figure 8 is reported (Federal Meteorological Handbook Number 2 "Synoptic Code", U. S.

Dept. Commerce Washington, D. C., p B3-1, 1979).

This means that all but the synoptic coded observations of cloud in the U. S., Canada, etc., are archived in tenths of sky cover, whilst those in Europe and many other countries are now archived in oktas, but were, until the early 1950s, archived in tenths. There are odd occurrences of other units of measurement including percentages and quarters of sky cover. It is for these reasons that total cloud amounts are given in tenths and, more importantly, that the more recent period (post 1955) has, so far, remained uninvestigated.

Table 4. Conversion from tenths to oktas of cloud cover and associated okta reporting codes

Code Figure	Fraction covered in tenths	Fraction covered in oktas
O	Zero	Zero
1	1 or less but not zero	1 Okta or less but not zero
2	1 and 3	2
3	4	3
4	5	4
5	6	5
6	7 and 8	6
7	9 or more, but not 10	7 or more, but not 8
8	10	8
9	Celestial dome obscured, or cloud amount cannot be estimated	

4.3 Observer training

It is presumed that observers working at the stations used in the historical study described earlier had enjoyed some degree of training and had accumulated experience; both of which are essential prerequisite for accurate recording. However, it is possible that traits common in observations made by untrained observers may be present to some degree in these observations.

The most likely systematic bias seems to be underestimation of thin cirrus cloud by inadequately trained observers. There is anecdotal evidence that rural sites reported less high cloud than meteorological observatories (presumably with better trained staff) in the first quarter of this century. We have not yet found any evidence to support this claim although it might be possible to undertake a detailed examination of a few paired station records for which cloud type as well as total amount is recorded.

It is reasonable to assume that the advent of air traffic increased observer training and, thus, that the record may be less reliable before the 1930s. On the other hand, cloud observing and reporting for aircraft may itself involve biases. For example, Garrod (1986) has suggested that surface observers underestimate the height of cumulus clouds.

One reason proposed for this systematic underestimation of cloud height is that observers trained at airports are encouraged to underestimate height on safety grounds. Untrained observers do not consider this and often estimate heights more correctly but lack of training seems to result in cloud lying above an obviously low layer as being perceived as being higher than it is.

It is commonly believed that untrained observers overestimate the importance, and hence the coverage, of clouds near the horizon. In particular, untrained observers will incorrectly identify a line at an elevation angle of 45° as dividing the sky dome area into equal parts whereas the correct elevation angle of such a dividing line is only 32.7°.

The "Moon illusion" is that which makes the Moon appear about four times as large at the horizon as at the zenith. The theories attempting to explain this phenomenon may also "explain" this overestimation of cloud cover at the horizon. The most common explanation (Rees, 1986) is that the horizon is perceived as being more distant than the zenith. This is thought to be because of intervening terrain before the horizon. The brain then interprets the constancy of angular diameter as an increase in the size. It has been suggested that normal perspective to the horizon increase the apparent size of the Moon. Further theory into Moon size is the gap between it and the horizon. When small, the Moon is compared to the terrain and appears large. The earliest theory suggested that objects appear larger when viewed ahead rather than above because of physiological effects linked to the position of the eyes in the head.

There is every reason to believe that the Moon illusion and reasons for it will also influence those observing some clouds. Theory indicates that the cloud would have to be a distinguishable form the brain would relate to terrain such as a cumulus or a bank of frontal cloud not extending toward one's zenith. The illusion would probably have a smaller impact upon the observation of amorphous clouds, such as stratus and nimbostratus, which usually fill the entire field of view and prevent the subconscious comparisons necessary for the effect to occur.

In a survey of about 100 randomly selected untrained personnel these two hypotheses were examined: (i) overestimation of the area of sky near the horizon and (ii) comparative distance estimation of the zenith compared with the horizon (the sky dome shape). The survey was undertaken at a location which offered a fairly clear view of the sky dome but included a number of vertically extended "obstacles". The sky dome during the survey included 5 to 7 oktas of broken, multi-layered stratocumulus.

Questionnaire results indicated that these untrained observers are surprisingly accurate in their estimates of sky areas; although this was only true when a percentage, rather than okta, scale was used. The experiment was designed to investigate the estimation of areas around the horizon. The use of a percentage scale seems to have removed the bias associated with any single value and considerably improved precision. The accuracy was greater when the sky fraction obscured was smaller and was influenced by changing from a standing to a lying position, which seemed to decrease the estimate. This was probably caused through the lowest sky fraction being out of view and may have an effect upon the estimation of sky areas near the horizon.

4.4 Man-made clouds

Over the last three decades anthropogenerated clouds have been reported formed predominantly by persisting jet aircraft condensation trails (e.g., Murcray, 1970). There is no ambiguity in reporting procedure, inasmuch as condensation trails are considered as cloud if they exist in the sky dome at the time the observation and report is made. More specifically the fraction of the celestial dome covered by condensation trails and cloud masses that have obviously developed from condensation trails, are included in the values reported for cloud amount as follows.

(i) rapidly dissipating condensation trails are not included,

(ii) persistent condensation trails and cloud masses obviously developed from condensation trails are included,

(iii) in the SYNOP reporting code this occurrence is indicated by adding the contraction "COTRA" at the end of the message. (Federal Meteorological Handbook, Number 2, 1979, p B3-1).

The ease of identification of contrails and their persistence prompted early investigations of the potential radiative, and hence climatological, impact of aircraft condensation trails (Reinking, 1968; Kuhn, 1970). However, estimation of the amount of sky covered is diffcult (e.g., Fig. 12).

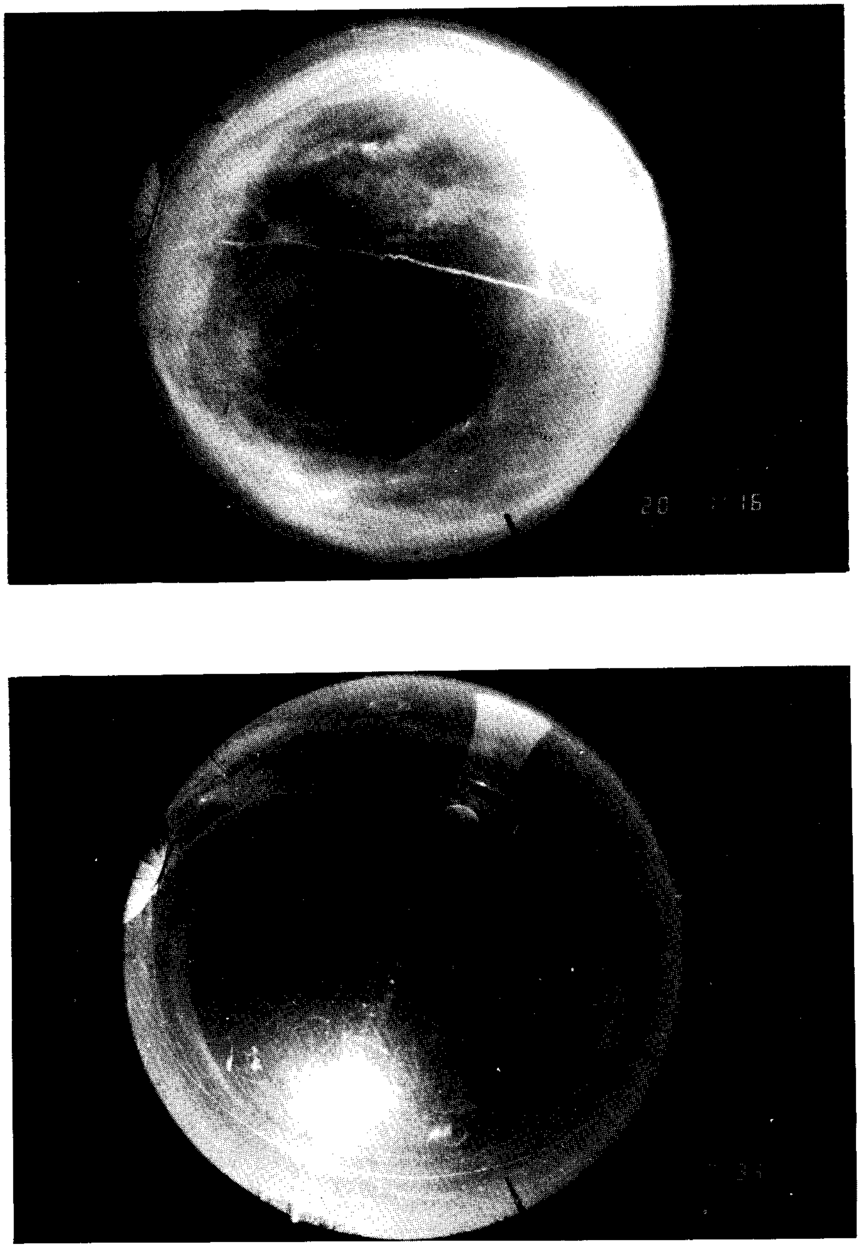


Fig. 12. All-sky camera images including jet aircraft condensation trails taken on 20th May and 5th March from one of the FIFE camera sites on the campus of Kansas State University, Manhattan, Kansas. The 20th May (01.16 GMT) photo (upper) contains one new trail while the 5th March (17.33 GMT) photo (lower) shows a substantial portion of the sky obscured by a trail which both diffused and persisted.

As part of the First International Satellite Land Surface Climatology Project Field Experiment (FIFE) currently taking place in Manhattan, Kansas, U. S. A. (Sellers *et al.*, 1988), a number of all-sky cameras are being operated. The pilot test period, between March and May of this year, has given rise to over 1200 all-sky images. These have not yet been analysed since retrieval of sky cover and cloud type and amount is a long and painstaking process. However, a preliminary survey shows that between 10 and 14% of these daylight photographs include jet contrails. This degree of anthropogenerated cloud would have a signficant impact on cloud amount investigations in regions of considerable commercial aircraft overflights. This increase in man-made clouds is another important reason why we have so far, resisted the temptation to investigate cloud amounts post 1954.

5. Diagnosing cloudiness change in a warming world

Before assessing the mean difference in cloud amount between the two periods (1901-1920 and 1934-1953) for the annual case and for the 4 seasons: March/April/May, June/July/August, September/October/November and December/January/February, it is necessary to establish whether there is any change in the variability between the two periods. The variability in cloud amount within each period about a 1:2:1 binomial filtered trend has been computed so that any changes in variability would be decoupled from possible (e.g., decadal) changes in mean values. This is the same methodology as employed by Lough *et al.* (1983) and Henderson-Sellers (1986a). In order to retain a 20 year filtered data set it was necessary to derive four more years' data: one at the beginnig and end of each period analyzed.

The F test was applied to establish, at a 1% significance level, which stations exibited a significant change in cloud variability between the cold and warm periods. The significance level for this test was set at 1% in order that a Student's t test applied at the 5% level would be valid on the mean differences as described below (e.g., Figs. 13 and 14)

Very few stations showed a significant change in cloud variability in the "warming world". Stations in the Indian sub-continent and Canada exhibit a somewhat higher failure rate than those in the earlier studies. For India, 10 failed in the annual case and 9, 12, 7 and 13 for MAM, JJA, SON and DJF respectively, while in Canada, 9 failed in the annual case and 6, 6, 8 and 6 for MAM, JJA, SON and DJF respectively. All stations for which the F test failed at the 1% level were excluded from the maps shown in Figs. 13 and 14.

The mean difference (cold minus warm) in cloud amount for the annual and four seasonal cases for the Indian sub-continent and Canada is shown in Figs. 13 and 14. The mean difference at each station has been divided by the normalized 40 year standard deviation at that station. In the case where some data were missing the means and standard deviation have been appropriately modified. The resulting contours are of the Student's t statistic and are shown at the 5% and 0.1% levels for both increasing and decreasing cloudiness.

The five maps in Fig. 13 show a considerable degree of consistency. The dominant trend is one of increasing cloudiness over much of the Indian subcontinent. The regions of increase and decrease do not appear to result from the shifting of any climatological pattern either temporally or spatially. The area of increase extends across much of the south and east of the region. A general area of decrease exists to the north of this, stretching from Bombay in the west, inland. There are also isolated areas of decrease in the north-east and north-west of the region. The trends in cloudiness noted for the Indian subcontinent do not exhibit signs of being due to a particularly obvious change in seasonal or spatial climatological patterns. The areas of change do not correspond well with the areas defined above with reference to the climatological influences upon cloudiness. Most significant and widespread is the change in cloudiness around the Bay of Bengal.

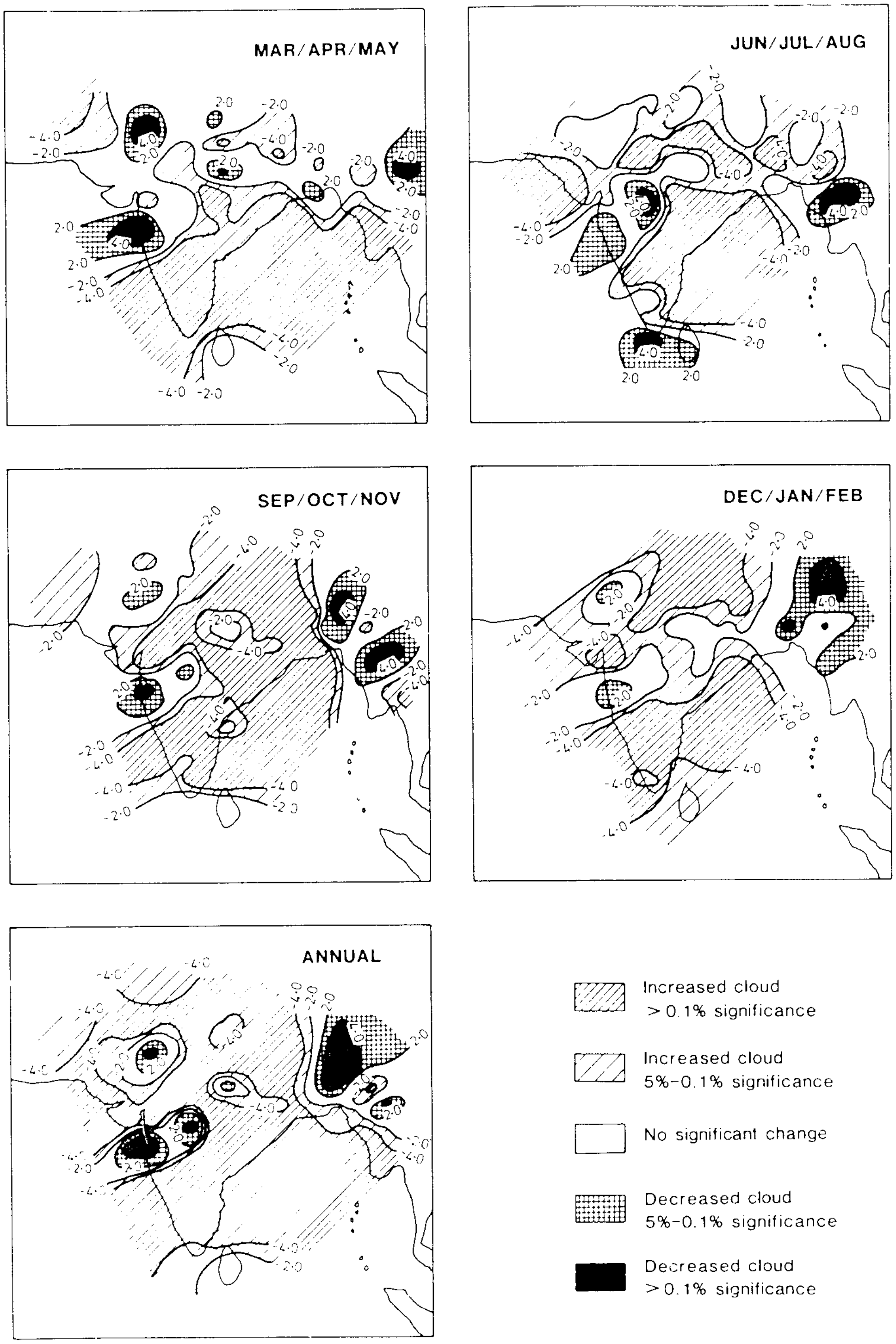


Fig. 13. Variation of the Student's t statistic for the Indian sub-continent generated from the mean differences (cold minus warm period) for the annual and seasonal cases. A negative difference (cold - warm) suggests an increase in cloudiness in a warmer world. The values at each station have been normalized by the stations standard deviation for the 40 years divided by $\sqrt{n}$ where n is the number of years for which valid data were available. While the zones of 5% significance have been shown to be statistically valid in additional test of the variances at a higher significance level would be required to demonstrate the validity of the 0.1% contours shown.

The Canadian maps shown in Fig. 14 are mutually consistent with statistically significant cloud amount increases across all of the region considered except on the east coast near the Gulf of St. Lawrence. These maps show greater spatial homogeneity than those for Europe and India; in this way they are similar to the U. S. A. significance maps in Henderson-Sellers (1986b). North America as a whole shows an almost overwhelming trend of increasing cloudiness.

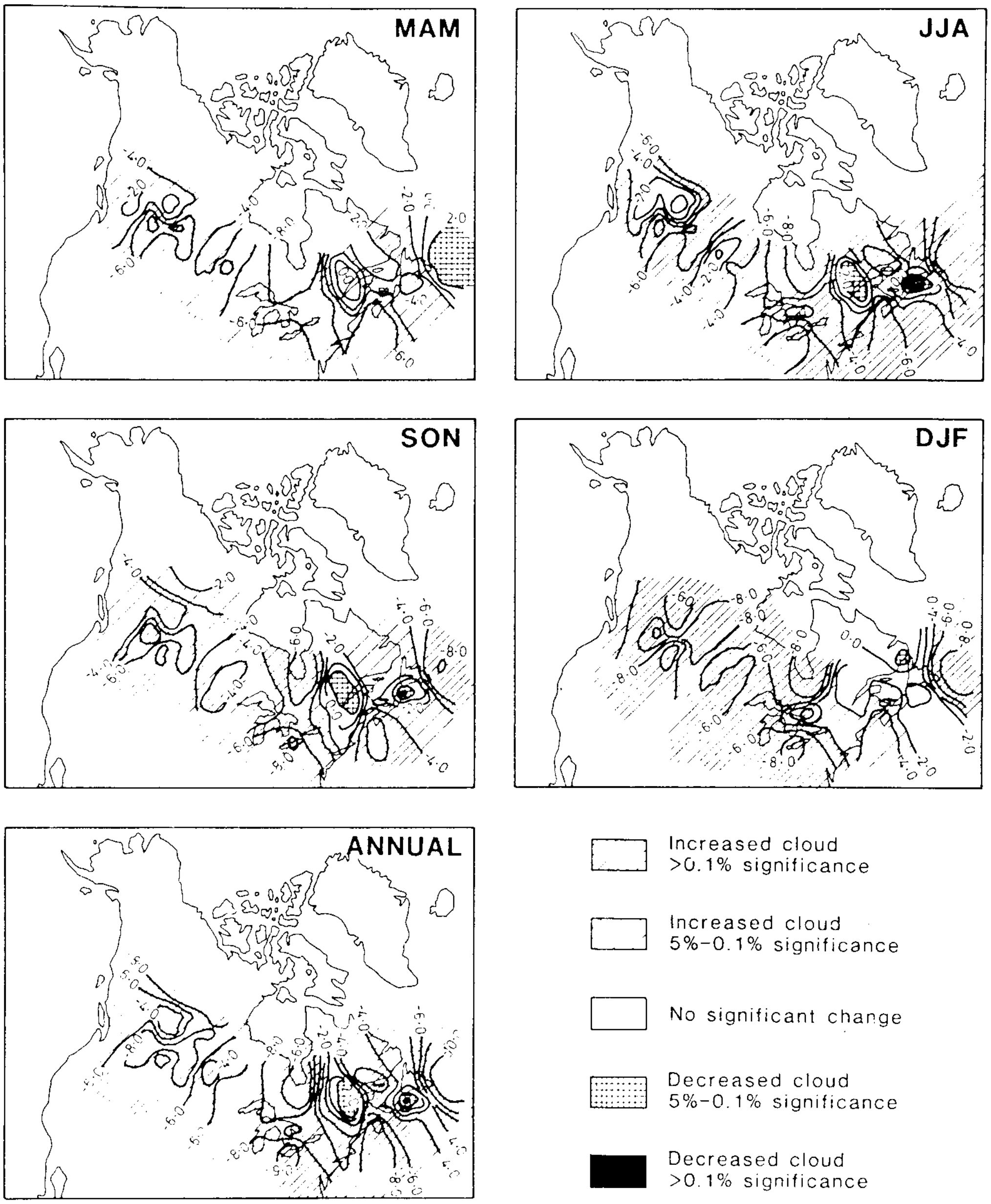


Fig. 14 Variation of the Student's t statistic for Canada generated from the mean differences (cold minus warm period) for the annual and seasonal cases. A negative difference (cold - warm) suggests an increase in cloudiness in a warmer world. The values at each station have been normalized by the station standard deviation for the 40 years divided by $\sqrt{n}$ where n is the number of years for which valid data were available. While the zones of 5% significance have been shown to be statistically valid an additional test of the variances at a higher significance level would be required to demonstrate the validity of the 0.1% contours shown.

6. Discussion

Surface-based observations of cloud amount have been recorded in many locations throughout this century (e.g., Hahn *et al.*, 1982, 1984). Although the observational scale used, the times of observation and the reporting procedures have been changed many times the observation of total cloud amount (i.e., the fraction of observer's sky-dome which is obscured from view by cloud) cannot have been affected so much that all the temporal trends described here are the result only of modifications in reporting procedure.

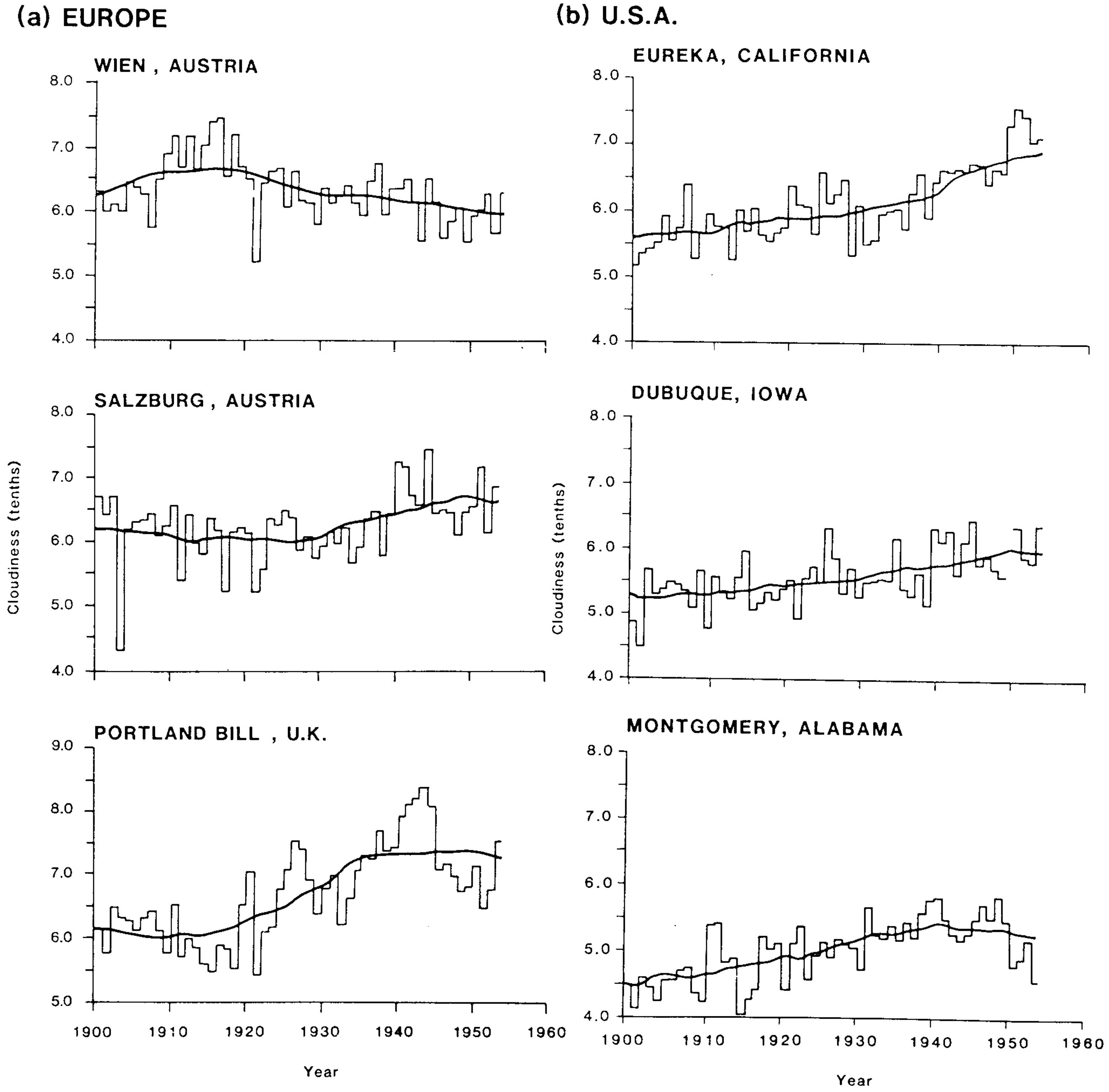
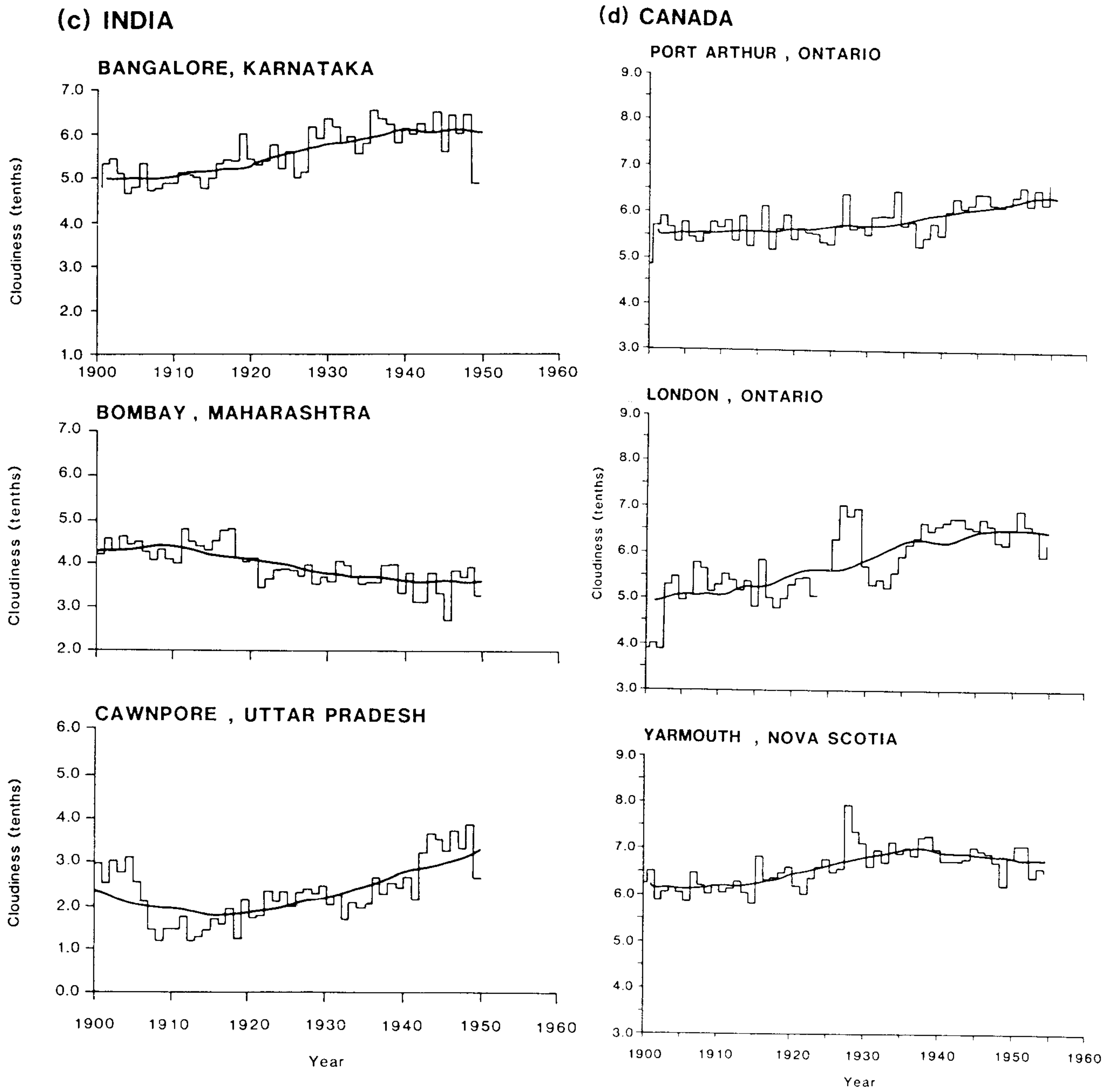


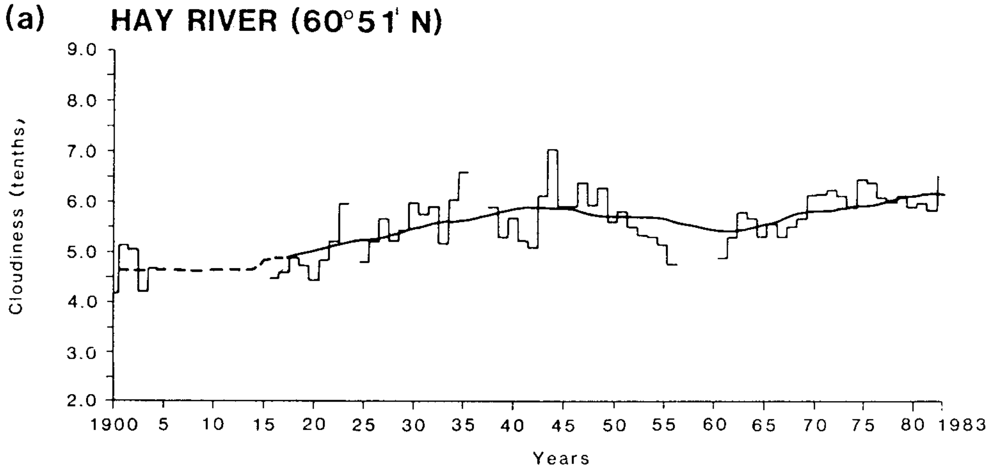
Fig. 15. Selected time series of cloud amounts (tenths) together with 20 year filtered curves. (a) Europe: Wien, Salzburg and Portland Bill. (b) U. S. A.: Eureka, Dubuque and Montgomery. (c) India: Bangalore, Bombay and Cawnpore. (d) Canada: Port Arthur, London and Yarmouth.



It is clearly possible that systematic changes in observing procedure are responsible for some of the identified cloud amount change. One method of trying to reduce the influence of such observing practice alterations would be to select warm and cold years from the same decade or twenty year period. Unfortunately this cannot be readily accomplished at a hemispheric or even a regional scale although it would be possible by undertaking a station by station co-analysis of temperature and cloud amount trends. Such a locally- specific investigation would negate an important feature of this investigation: the general tendency for total cloud amount to increase in a number of diverse areas *at the same time as hemispheric temperatures increased.*

Generally the total cloud amount data that have been examined show an increase in cloud amount between 1900 and the mid-1950s. Examples of time series from three stations for each of the four regions studied so far are shown in Fig. 15. There are, of course, exceptions to the increasing trend in cloudiness, for example, Vienna (Wien) in Europe (Fig. 15(a)) and Bombay in India (Fig. 15(c)), but the fifty five years' data archived exhibit relatively few such time series.

These results, and especially the cloud time series in Figs. 2 and 15, suggest that an investigation of the cloud amount patterns since 1955 would be worthwhile. The dashed curves in Figs. 2(c) and 2(e) indicate that for all of North America there is a continuing tendency for increased total cloud amount between 1954 and 1982. To bring all the station archives so far collected up to date would be a considerable undertaking. It has been suggested that a further investigation of the potentially vital characteristic of cloud type using the global analyses of Hahn *et al.* (1982, 1984). Unfortunately their land surface data tape is for 11 years only (1971 to 1982) and gives seasonal rather than monthly values for 5° × 5° grid areas. It is probable that no data trend could be established in such a short period of spatially and seasonally smoothed data. The alternative is for us to re-analyse the original cloud observations which they used and we are currently investigating this possibility.


(a) HAY RIVER (60°51' N)

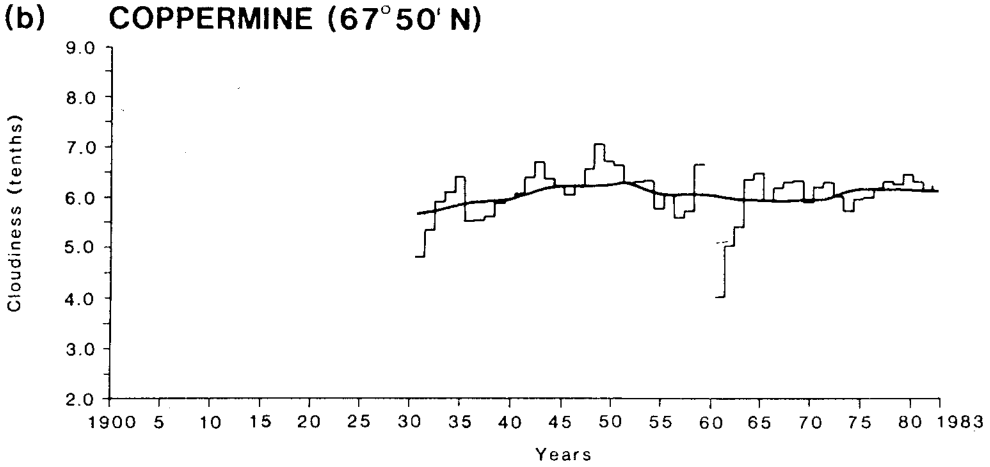

(b) COPPERMINE (67°50' N)

Fig. 16. Cloud amount time series and 20-year filtered values for (a) Hay River and (b) Coppermine from 1900 and 1931 to 1982.

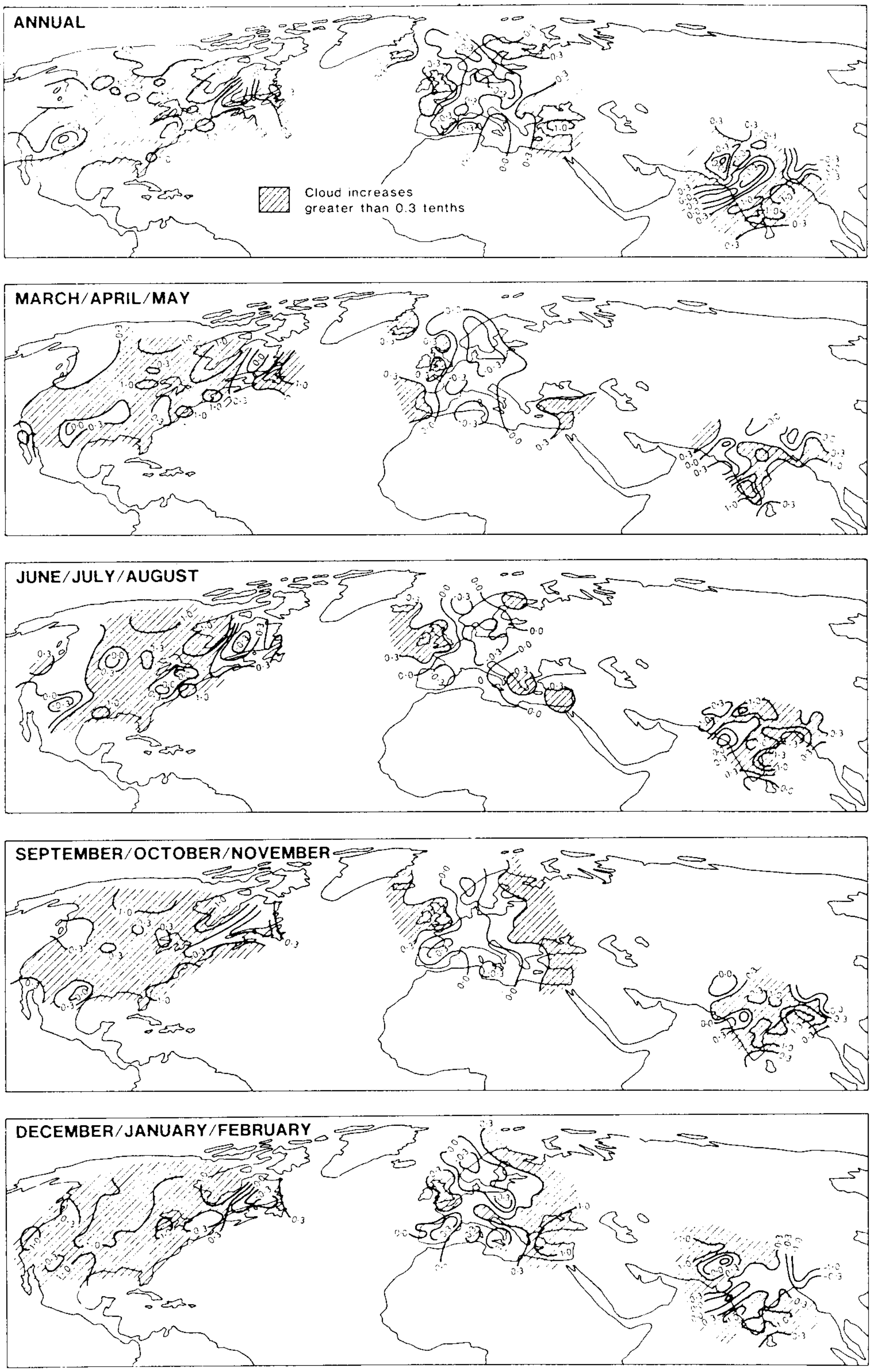


Fig. 17. Total amount charges "predicted" from the historical analogue "model" for (a) annual, (b) March/April/May, (c) June/July/August, (d) September/October/November, (e) December/January/ February cases. Values are of warm - cold periods i.e., positive values are cold amount increases in a warming world. A considerable area of the regions examined show cloud amount increasing by more than 0.3 tenths of sky cover.

Another strategy is to examine cloud amount trends in an area already identified as sensitive to climatic change induced by increases in CO_2 and other trace gases. We intend to try to continue the Canadian archive by incorporating station records from the Canadian Arctic (*cf.* Henderson-Sellers and McGuffie, 1989). A number of stations have been identified in the North West Territories and the Yukon which could offer adequate cloud records. Unfortunately, most of these stations began recording meteorological observations only in the late 1920s/early 1930s. Their data record cannot, therefore, be used in the type of historical analogue study described here but other time periods could be considered. Fig. 16 shows the record of total cloud amount observed at Hay River (60° 51′ N, 115° 20′ W) and Coppermine (67° 50′ N, 115° O5′ W) from 1900 to 1982. In future investigations it is hoped to examine these and other station records in the context of a warming Arctic.

It is unwise to suggest that results of any analogue model should be preferred to those from a physically-based model. The analogue, upon which the results described here are based, is none the less useful inasmuch as it is a transient climate shift in which temperatures increased globally by about 0.5 K. Fig. 17 shows the total cloud amount changes for the annual and seasonal cases "predicted" by this historical analogue model. It must be recalled that these computed cloud amount changes are generally statistically significant at the 5% level (*cf.* Figures 13 and 14 and Henderson-Sellers, 1986a, b). Thus, although the cloud amount increases are small, generally between 0.3 and 1.0 tenths of sky cover, they are real and may be an important feature of the climatic variations of the first half of this century. At the least, the predictions of cloud amounts and cloud changes made by physically-based numerical climate models should be examined in the context of these results.

7. Acknowledgements

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