CLOUD CHANGES IN A WARMER EUROPE

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Abstract. Cloud cover records for western Europe have been analysed in the context of the 'warming world' analogue model described by Lough *et al.* (1983). It is found that cloud cover has generally increased in moving from a cold period (1901–1920) to a warm period (1934–1953). The exception to this general trend is over the central part of the area considered (Germany, France and some parts of Spain) where there is a tendency towards decreasing cloud as warming occurs. While the results presented here are not closely correlated with the temperature and precipitation results of Lough *et al.* (1983), there is support for their hypothesis that cloudiness increased in autumn over northern Europe. The suggestion that successful performance of numerical climate models in seasonal simulations might demonstrate adequacy in other climatic simulation modes is also examined It is shown that whilst there is good agreement with observations in one such numerical model in the seasonal simulation, there is no agreement in the case of a 'warming world' in either the direction or the amount of cloudiness change.

1. Climate of a Warmer World

Probably the single most difficult climatic feedback process to measure and hence to model is the cloud-radiation feedback (GARP/JOC, 1978). It is well known that clouds affect both the incoming shortwave radiation, generally tending to increase the planetary albedo, and also the emitted terrestrial radiation tending to enhance the 'greenhouse effect' (Ohring and Clapp, 1980; Cess *et al.*, 1982). The question of which feature dominates probably varies as a function of cloud type, cloud height and cloud structure (e.g. Schneider, 1972; Shukla and Sud, 1981). There are additional difficulties in postulating likely cloud-climate interactions in perturbed climate situations, such as the inability to establish whether an increase in cloudiness, say as a result of increased temperatures and hence increased evaporation, leads to an increase in areal coverage by clouds (as in the case of increased stratiform clouds) or a decrease in areal extent associated with increased vertical extent (as in the case of cumuliform clouds). The semi-transparent nature of cirrus cloud and the dynamic nature of overlap of layered clouds make even simplified studies of cloud-climate interactions difficult (Stephens and Webster, 1979; Webster and Stephens, 1984).

The cloud-climate feedback is particularly difficult to understand because there are considerable problems associated with *both* the observation of cloud and the successful parameterisation and hence prediction of clouds in climate models. The latter difficulty is exaggerated by the lack of adequate data which is the result of the former problem. For example, Hansen *et al.* (1984, p141) state that: 'Clearly, assessment of the cloud con-

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tribution to climate sensitivity depends crucially upon development of more realistic representation of cloud formation processes in climate models, as verified by an accurate global cloud climatology'. Efforts are being made to improve the cloud observational data base (e.g. Stowe, 1984) but projects such as the International Satellite Cloud Climatology Project (ISCCP) (Schiffer and Rossow, 1983), even when successfully completed, will provide only a five year data set. In addition satellite-based cloud retrieval projects are unlikely to be able to furnish adequate information about cloud layering and cloud type and the fundamental difference between satellite and surface based cloud observations precludes, 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).

It seems likely that the increase in the concentration of atmospheric carbon dioxide over pre-industrial levels caused predominantly by the combustion of fossil fuels will lead to increased temperatures (NAS, 1982). The atmospheric carbon dioxide concentration is presently about 340 ppmv as compared with various estimates of the pre-industrial concentration ranging from 260 to 290 ppmv (e.g. Brewer, 1978; Chen and Millero, 1979; Wigley, 1983). Predictions of the likely atmospheric concentration of carbon dioxide for the year 2025 range from 440 to 600 ppmv, depending upon the forecast growth rate of energy used (Wigley, 1982). It is for this reason that climate modelling studies generally investigate the effect of doubling the atmospheric concentration of carbon dioxide. Such studies suggest that a doubling of atmospheric CO_2 will produce an increasing global mean temperature of 2–3 °C (Gates, 1980; NAS, 1982).

Many of the climate model investigations of the likely impact of the increased atmospheric CO_2 use specified cloud cover (e.g. Manabe and Wetherald, 1975; Mitchell, 1983). This is clearly an unsatisfactory state of affairs but one which can, perhaps, be viewed sympathetically in the light of the difficulties of parameterising cloud processes successfully in climate models. Some investigations have been undertaken with models which include cloud prediction and hence cloud climate feedback (e.g. Washington and Meehl, 1984). One of the most recent of these, by Hansen *et al.* (1984), finds a greater climate sensitivity to doubling atmospheric CO_2 than e.g. NAS (1982) with global mean temperatures increasing by between 2.5 and 5 °C. Hansen *et al.* (1984) note that the physical process contributing the greatest uncertainty to their predicted climate sensitivity on a timescale of 10–100 yr appears to be the cloud feedback.

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). It is this analogue method which is employed here.

2. Analogue Model for a Warming World

The construction of analogue models with which to investigate the probable effects of increasing atmospheric CO_2 was pioneered by Flohn and Kellogg in 1977 and has been reviewed recently by Pittock and Salinger (1982). Wigley *et al.* (1980) composited data from individual years 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.

Lough *et al.* (1983) selected the warmest and coldest twenty-year periods from the gridded northern hemisphere temperature data produced by Jones *et al.* (1982). These data are illustrated in the form of anomalies from a 1946–1960 reference period in Figure 1. Similar temperature variations for the world's oceans have recently been identified by Folland *et al.* (1984). In selecting the 20-yr warm and 20-yr cold periods only the temperature data for the period 1901–1980 inclusive were considered by Lough *et al.* (1983). The warmest 20-yr period is from 1934–1953 and the coldest from 1901–1920 (Figure 1). The northern hemisphere annual mean surface air temperature differed by 0.4 °C between these two periods. 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 undertaken by e.g. Wigley *et al.* (1980) and Jäger and Kellogg (1983). 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 indeed be associated with the increase in atmospheric CO_2 during the early part of the twentieth century. Lough *et al.* (1983) investigate the changes in temperature and precipitation in their warming world discussion, using these to identify the possible economic impact due to perturbations in energy demand and growing season length.

In this paper surface based observations of cloud have been investigated employing the historical analogue method and using the warm and cold periods identified by Lough *et al.* (1983). However, caution must be exercised when using this method and in particular when applying it to the topic of cloud changes. The fact that hemispheric mean temperatures fell by 0.3 °C in the 30 yr (1945–1975) when atmospheric CO_2 concentrations were increasing most rapidly 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 over the last century (Schlesinger and Wigley, 1985) which allow 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 only approximately half of the observed warming of 0.4 °C can be confidently attributed to CO_2. There is no guarantee that the other factors contributing to the observed warming (perhaps long term but eventually random fluctuations in ocean temperature) would produce the same changes in cloudiness found with increased CO_2. For example, with enhanced CO_2, the continents would be expected to warm faster than the oceans, whereas with a warming 'driven' by the ocean, the opposite might be true, and then the changes in cloud would be different, especially near coasts. Despite these caveats this investigation of cloud amounts offers a link between increasing atmospheric CO_2 and cloudiness which is an alternative to numerical modelling results.

3. The Cloud Data

Cloud data were taken from the records of meteorological observations at observing sites

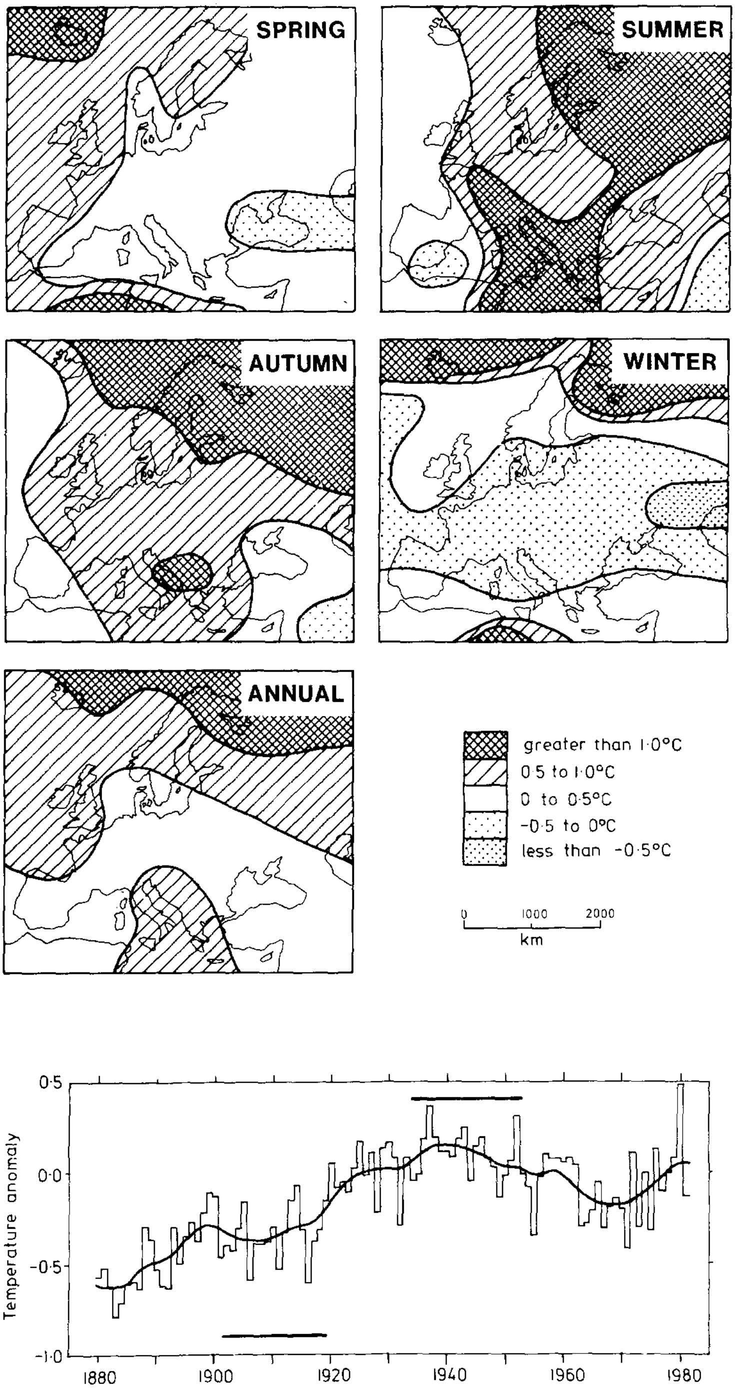


Fig. 1. (a) Temperature differences, warm period minus cold period as computed by Lough *et al.* (1983). (b). Northern hemisphere mean surface air temperature variations (K) shown as anomalies from 1946–60 reference period. The curve is of 20 yr filtered values. The warm and cold periods used here are marked (after Lough *et al.*, 1983).

in Europe which are held in the British National Meteorological Library. The data sources consulted are listed in Table I. It was necessary to use this somewhat unsatisfactory data source as cloud observations are not included in the World Weather Record. The aim was to construct a warming world analogue model for cloudiness for the area of Europe previously analysed for temperature and precipitation by Lough *et al.* (1983). Sixty stations were selected in the first instance although two of the data sets, which turned out to be largely incomplete, were eliminated from the subsequent analysis (Table II).

The attempt to find sixty stations which gave as good a spatial coverage of the area under investigation as possible and which also contained a complete or almost complete data record for the two twenty year periods was fraught with difficulties. Not all European countries archived meteorological records in national meteorological reports even as recently as the first quarter of this century. In particular data for Italy are difficult to find as individual observatories archived and disseminated their own data until very recently. In addition the warm and cold periods selected include both world wars during which, even if meteorological observations were made, they were often not included in national meteorological reports either because they were not archived or because the surface station was in the hands of another nation.

The difficulties remarked upon above relate only to finding stations which offer fairly complete temporal coverage and an adequate distribution spatially. Establishing cloud amounts for the two periods involved other difficulties. Cloud observations were not made in the same units, nor were they made at the same times of day over the whole of

TABLE I: Sources of Cloud Data

Pubblicazione dell'Osservatorio astronomico de Brera in Milano, Ulrico Hoepli Editore-Librano Milano.

Sverigies Meteorologiska Och Hydrologiska Institut, Månadsöversikt over väderlek och vattentillgång, Nederbörden i Sverige, Meteorologiska iakttagelser i Sverige, Hydrologiska iakttagelser i Sverige, Vattenstånden vid Sveriges kuster, Stockholm.

Meteorologiska Iakttagelser i Sverige, Utgifria af Kongl. Sveriska Vetenskaps-Akademien, Anstälbda och utarbetade under inseende af Meteorologiska Central-Anstatten, Fyrtioandra Bandet.

Institut Meteorologic Central al României, Publicatiuni oficiale conduse de E. Otetelsianu director, Buletinul Luner al Observatuinilor Meteorologice din România, Bucaresti.

Ministerul, Anriculterei, Industriei, Comerciuli si Domeniilor, Institutul Meteorologic al Romaniei, Analele Institutulue Meteorologic al Româiei, Publicate de Stefan C. Hepiles si I. St. Murat.

Institutul Meteorologic al Republicii Populare Române, Buletinul Lunar al Observatilor Meteorologice din R.P.R., Intreprindearea Poligrafica, Bucaresti.

Institut Météorologique Central de Bulgarie, Annuaire de l'Institute Météorologique de Bulgarie, Sofia Imprimerie de l'état.

Jahrbücher der Zentralstalt für Meteorologie und Geodynamik, Amtliche Veröffentlichung, Österreichischen Staatsdruckerei in Wien.

Publikationer fra det Danske Meteorolgiska Institut Charlottenlund Årbøger, Trykt I Hørsholm Bogtrykkeri, Danmark.

Meteorologisk Aarborg, Danske Meteorologiske Institut, Kjøbenhavn Trykt i Bianco Lunos Bogtrykken Autograferet of C. Ferslaw and Co. I Kommission hos

Universitetsboghandler G.E.C.

Institut Hydrométéorologique, Annuaire des observations de stations météorologique de la république Tchecoslovaque, Hydrometeorologicky Ustav, Praha.

Meteorologische Zentralstatt für Böhmen und Mähren, Jahrbuch der Meteorologischen Beobachtungen, Praha.

Magnetische und Meteorologische Beobachtungen an den K.K. Stemwarle zu Prag, Prag K.U.K. Hofbuchdruckerei A Haasse-Selbstverlag.

Reykjavik Manadaryfirlit Sarnin A Vedurstofunni, Iceland.

Annulaire Météorologique d'Islande, Météorologique de löggildingarstofan, Reykjavik.

Gibraltar Meteorological Observations, HMSO, London.

Cyprus Meteorological Observations, HMSO, London.

The Weekly Weather Report of the Meteorological Office, HMSO, London.

The Monthly Weather Report, HMSO, London.

Malta General Abstract of Meteorological Observations, Malta University Observatory.

Norsk Meteorologisk Årbok, Morske Meteorologiske Institut, Tryk Hos Grøndahl and Søn, Oslo.

Jahrbuch des Norwegischen Meteorologischen Instituts, Kristania Druck bei Gröndahl und Sön, Oslo.

Annales du Bureau Central Météorologique de France, Gauthrer-Villars, Imprimeur-Librarie, Paris.

Bulletin Mensuel de L'office National Météorologique de France, Gauthrer-Villars, Imprimeur-Librarie, Paris.

Bulletin Annuel du service météorologique de la métropole et de l'Afrique du Nord, Paris.

Jahrbücher der Königl. ung. Reichs-anstatt für Meteorologie und Erdmagnetismus, Offizielle Publication, Budapest.

Annales de l'Institut Météorologique Hongrois, Publication Officielle, Budapest.

Meteorological Observations in Egypt, Ministry of Defence, London.

Ministry of Public Works, Egypt, Physical Department, Meteorological Reports, Government Press, Cairo.

Observations d'Alger Université, Algeria.

Résumé Mensuel du temps en Algeria, Imprimeur-Librarie, Paris.

Royaume de Grèce Ministère de la Défense Nationale, Service National Météorologique section climatologique, Bulletin Mensuel Climatologique.

National Observatory of Athens Meteorological Institute, Climatological Bulletin, Athens.

Meteorological Yearbook of Finland, Climatological Data, Finnish Meteorological Office. Helsinki.

Observations publiées par l'institut météorologique central de la société de Finlande, Helsingfors, Imprimerie des Héritiers de Simalius.

Servico Meteorologico Nacional, Anuano Climatologico de Portugal, Lisboa.

Observaoes Meteorologicas e Magneticas Feitas no Observatorio Meteorologico de Coimbra, Coimbra Imprensa da Universidade.

Universidade de Lisboa, Annals do instituto Geofisico do Infante D Luts, Lisboa.

Deutsches Meteorologisches Jahrbuch, Karlsruhe.

Die Ergebnisse der Meteorologischen Beobachtungen, Karlsruhe.

Deutscher Wetterdienst, Deutsches Meteorologisches Jarhbuch, Bundesrepublik, Bad Kissingen.

Koninklijk Nederlandsch Meteorologisch Instituut, Jaarboek, Rijksuitgeverij 's-Gravenhage.

Boletin Mensuel del Observatorio de Cartuja Granada, Observaciones meteorologicas, Granada.

TABLE II: List of stations used including location, record length and hours at which observations were made

	+Ht(m)	Latitude	Longitude	Location	Comments	Observation times*
U.K.						
Aberdeen	338	57° 08′ N	2° 08′ W	on the coast, near mountains	Braemar (57° 01′ N, 3° 24′ W) from 1948	Reports vary from 1 to 5 times with both time and station.
Oxford	65	51° 46′ N	1° 16′ W	flat land		
Portland Bill	11	50° 32′ N	2° 27′ W	on the coast, relatively flat land		
Scilly (St. Mary's)	48	44° 56′ N	6° 18′ W	island		
Denmark						
Vestervig	19	56° 46′ N	8° 19′ E	on the coast, flat		08, 14, 21 1938–1953
Fanø	3	55° 27′ N	8° 24′ E	on the coast, flat		
Bøgø	25	54° 56′ N	12° 03′ E	on the coast, flat		
Hammersthus	10	55° 17′ N	14° 47′ E	island	changes to Sandvig in 1951	
Norway						
Bergen	43	60° 24′ N	5° 19′ E	on the coast, near hilly area	location change in 1904 *from* 60° 23′ N, 5° 21′ E *to* 60° 24′ N, 5° 19′ E	08, 14, 19 1937–1948 07, 13, 19 1949–1953
Ona	11	62° 52′ N	6° 33′ E	coastal region, near hills		
Tromso	102	69° 39′ N	18° 57′ E	coastal region		
Karasjok	131	69° 28′ N	25° 31′ E	inland, hilly but not mountainous		

Table II (continued)

	+Ht(m)	Latitude	Longitude	Location	Comments	Observation times*	
Holland							
De Bilt	3	52° 06′ N	5° 11′ E	flat	for *all* stations monthly averages in later period (1934–1953) are reported as *tenths* (i.e. to only one significant figure).		
Oudenbosch	2	51° 35′ N	4° 32′ E	flat			
Winterswijk	33	51° 58′ N	6° 43′ E	flat			
Groningen	9	53° 13′ N	6° 33′ E	flat	replaced by Van Eelde in Feb. 1952		
Sweden							
Lund	37	55° 42′ N	13° 12′ E	coastal surrounded by flat land		08,14,21 08,14,19 07,13,19	1912–1940 1941–1946 1947–1953
Stockholm	44	59° 21′ N	18° 03′ E	coastal surrounded by flat land			
Iceland							
Grimsey	22	66° 32′ N	18° 01′ W	island			
Stykkisholmur	26	65° 05′ N	22° 44′ W	coastal			
Faeroes							
Thorshavn	20	62° 02′ N	6° 45′ W	on very small island	(62° 02′ N, 6° 45′ W becomes Hojvig 62° 03′ N, 6° 45′ W in 1934)	08,14,21	1938–1953
Finland							
Mariehamm	4	60° 07′ N	19° 54′ E	island			
Kuopio	232	62° 54′ N	27° 39′ E	inland, surrounded by flat land	Kuopoi Maurato (62° 54′ N, 27° 39′ W) in 1942 to Kuopio Puijo (62° 55′ N, 27° 40′ W)		

Table II (continued)

	+Ht(m)	Latitude	Longitude	Location	Comments	Observation times*	
					Kuopio Puijo replaced by Rissala (63° 00′ N, 27° 48′ W) *from* 1951		
Oulu	17	65° 01′ N	25° 24′ E	coastal, flat land			
Austria							
Wien	203	48° 15′ N	16° 22′ E	inland, near Alps		07,14,21	1908&1909
Graz	369	47° 04′ N	15° 28′ E	inland, near Alps			
Salzburg	436	47° 58′ N	13° 00′ E	inland, near Alps			
Innsbruck	582	47° 16′ N	11° 24′ E	inland, near Alps			
Cyprus							
Nicosia	159	35° 09′ N	33° 22′ E	hilly island		08,14	1934–1953
Limassol	17	34° 41′ N	33° 03′ E	hilly island		08,14	1934–1953
Italy							
Milan	147	45° 28′ N	9° 12′ E	inland, near Alps			
Hungary							
Debrecen	114	47° 30′ N	21° 38′ E	inland, flat land			
Magyar-Ovar	122	47° 53′ N	17° 16′ E	inland, flat land			
Szeged	79	46° 15′ N	20° 09′ E	inland, flat land	46° 15′ N, 20° 09′ E replaced by Csonograd 46° 40′ N, 20° 10′ E, for year 1945		

Table II (continued)

	+Ht(m)	Latitude	Longitude	Location	Comments	Observation times*	
Portugal							
Lisbon	77	38° 43′ N	9° 09′ W	coastal		09,15,21 06,12,18	1938–1945 & 1947–1953 1946
Coimbra	140	40° 12′ N	8° 25′ W	slightly inland, close to hilly area		09,15,21	1938–1953
Greece							
Athens	103	38° 03′ N	23° 40′ E	coastal; country is quite mountainous	In 1945 Athens changes from Athinaiville (34° 59′ N, 23° 44′ E) to Athinai Philadelphia (38° 03′ N, 23° 40′ E)	08,14,20 08,14,20	1934–1939 1952–1953
Patrai	3	38° 15′ N	21° 44′ E	slightly inland; country is quite mountainous		08,14,20	1934–1939 &1952 & 1953
Tripolis	~700	37° 31′ N	22° 21′ E	inland; country is quite mountainous	data missing during 2nd World War. Arta doesn't appear again	08,14,20	1934–1939 & 1952 & 1953
Arta	~60	39° 10′ N	21° 02′ E	inland; country is quite mountainous		08,14,20	
Larisa	72	39° 38′ N	22° 25′ E	inland; country is quite mountainous		08,14,20	
France							
Toulouse	151	43° 37′ N	1° 22′ E	inland, near Massif Centrale and Alps and Pyrenees	missing data during 2nd World War	06,09,12,15,18,21,24 09,12,15,18	1901–1907 1908–1914

Table II (continued)

	⁺Ht(m)	Latitude	Longitude	Location	Comments	Observation times*	
Nantes	41	47° 15′ N	1° 34′ W	slightly inland, relatively flat	missing data during 2nd World War	01,04,07,10,13,16,19,22 06,09,12,15,18,21,24 06,09,12,15,18,21,24	1901&1902 1903 1904–1914
Spain							
Granada	774	37° 11′ N	3° 35′ W	slightly inland, in hilly area	1908–1915 1934–1953	07,14,21 07,13,18	1908–Jul 1947 Aug 1947–1953
West Germany							
Hamburg	14	53° 38′ N	10° 00′ E	coastal, flat	missing data during war – Freiburg appears very little after the 2nd World War	07,14,21	1953
Karlsruhe	115	49° 01′ N	8° 23′ E	inland, flat			
Freiburg	267	48° 00′ N	7° 51′ E	inland, hilly			
Regensburg	337	49° 02′ N	12° 04′ E	inland, flat			
Bayreuth	358	49° 58′ N	11° 34′ E	inland, flat			
Gibraltar							
Gibraltar	15	36° 09′ N	5° 21′ W	coastal, surrounded by mountains of N.Africa and Spain	no data before 1909 (2nd World War data bound in U.K.Met.Off.)	07,13,21 07,13,18 00,06,12,18 03,09,15,21 03,09,15,21	1916–1920 1938–1943 1944 1945&1946 1948–1953
Czechoslovakia							
Prague	191	50° 05′ N	14° 25′ E	inland, in between Alps and Carpathians	missing data during 2nd World War		

Table II (continued)

	$^{+}$Ht(m)	Latitude	Longitude	Location	Comments	Observation times*	
Malta							
Malta (University)	–	35° 51′ N	14° 28′ E	island	no data before 1914 (2nd World War data bound in U.K.Met.Off.)	01,07,13,18 00,06,12,18 03,09,15,21	1939–1943 1944 1945–1948
Rumania							
Turnu-Severin	70	44° 38′ N	22° 41′ E	inland; country quite mountainous	1911 and 1917–1920 missing		
Constanta	30	44° 11′ N	28° 39′ E	inland; country quite mountainous	Constanta Aero becomes Constanta Palas in 1948 Constanta Palas becomes Constanta Reg in 1952		
Dorohoi	150	47° 29′ N	26° 31′ E	inland; country quite mountainous	47° 29′ N, 26° 31′ E-replaced by Botosani 47° 44′ N, 26° 41′ E from Nov. 1944 until Sept. 1946 and for M,A,M 1947		
Bulgaria							
Sofiya	550	42° 42′ N	23° 20′ E	inland, situated in hilly area	1906–1920 1934–1939	07,14,21	1906–1937
Algeria							
Algiers	38	36° 47′ N	0° 44′ E	coastal, near Atlas mountains	1901–1914 1938–1939	07,13,17	1901–1951
Egypt							
Port-Said	4	31° 16′ N	32° 19′ E	coastal quite flat	1901–1920 1934–1947	07,14,17 08,14,20	1901–1914 1935–1940 & 1946 & 1947

Stornoway and Holyhead (U.K.) finally omitted from data set because observations cease being recorded in 1909.

* Where no indication is given only one monthly mean value was reported. Times given are those recorded.

\+ Heights are in metres above mean sea level.

Europe. Generally the archived data are in tenths of sky cover although percentages are also employed, eighths begin to be used towards the end of the second period in some places and one station (Malta) reports quarters of skycover in parts of the first period. Even when the quantitative scale is the same there are differences in reporting procedures which can only be seen when two, apparently independent organizations record cloud amounts for the same location. This occurred for a few stations and although the reported values were similar they were rarely exactly the same. Some national archives give a single number for monthly averaged cloud amount with no information about whether this is an average of one observation taken each day or a monthly average of diurnally averaged cloud observations. Other national agencies indicate the number, and sometimes the time, of the observations which are averaged to compose the monthly mean and other meteorological services give monthly averages at a number of times of day although these times do not coincide and often vary through time (Table II). Very few archives specify whether the observation times are GMT, local solar or local time.

Since the data available for inclusion in monthly means ranged from one observation per day to up to 7 observations a day and the area studied spans $\lesssim$ 3 hr in local solar time, the only methodology seemed to be to average all the available data on a monthly basis for each of the identified stations. It is clear that this simplistic approach of incorporating all available data, whilst being the only way of gaining adequate spatial coverage, has degraded the data source by including a diurnal range in some station averages whilst such a range is not incorporated into all averages. The only alternative would have been to try to establish monthly mean cloud amount at a single time of day. This was, however, impossible since a number of national agencies stated that cloud data were composed of a number of observations but these individual observations were not available and in addition a few stations did not observe at 'obvious' times such as 0900Z. In any case it is arguable that a diurnal average is preferable to cloud information pertaining only to one time of day and so, in this sense, the data base can be considered to have been enhanced by the inclusion of as many observing times as possible at each station.

Where data were given in quarters, eighths or percentages these were converted to tenths. Where data were missing from a station record this void was noted and account was taken in constructing means, variability etc. The data record is fairly complete, containing gaps of less than two years in all but a very few cases. The station records which contained less data than this, such as Sofiya, were noted and results for these stations were treated with great caution in the subsequent analysis.

It is well established that changes such as increasing urbanisation have affected meteorological records in many areas (Chandler, 1976; Palumbo and Mazzarella, 1984). This is a factor which must be borne in mind since any trends caused by, for example, the changes in viewing conditions from the meteorological station or locally increasing temperatures cannot be removed from the data set used here. In addition the data sets include various substitute stations. These were chosen as carefully as possible so as to be very close to the original station; for example, Aberdeen (57° 8′ N, 2° 8′ W) which is replaced by Braemar (57° 1′ N, 3° 24′ W) from 1948. If no suitable substitute could be found the station was removed from the record and another sought to replace it for the entire study period. Details of substitutions are given in Table II. It is also possible that station locations have been moved by small distances perhaps in an attempt to overcome the effects of increasing industrialisation or urbanisation. None of these factors have been considered here, although any or all of them could in part explain some of the anomalies described below.

Any use of surface-based observations of cloud amount necessitates assumptions about the accuracy of the observations. It is well established that cloud observations even by trained meteorologists will differ from individual to individual (e.g. Merritt, 1966). However there is less discrepancy between reports of total cloud amount than between assessment of cloud type and height. Also there is unlikely to be a bias in the reports used here so that monthly means and hence the seasonal and annual averages analyzed should be 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. Thus an optimal spacing of observing sites (in ideal conditions) would be on a grid of dimension ~100 km. Unfortunately the other prerequisites precluded such an optimization in station choice here. Despite these problems the 58 stations retained in the data set offer fairly good spatial coverage (Figure 2) and excellent temporal coverage (Table II) in all but a few cases.

The characteristics of the cloudiness data for the cold and warm periods are illustrated in Figures 2 and 3. Histograms of percentage frequency of occurrence of cloud amount in tenths are shown for both periods in Figure 2. This type of representation of cloud data has been used to characterize cloudiness regions (e.g. Barrett and Grant, 1979). The histograms show a large spatial variation from predominantly 8–10 tenths cloud to the north and west grading through a more 'bell-shaped' distribution to histograms dominated by 0–3 tenths in the south, especially the south east of the region. This trend from generally cloudy conditions in the north to much clearer skies in the south is also apparent in the contour plots of seasonal and annual cloud amount for the two periods (Figures 3(i) and 3(ii)). The seasonality in cloud amount also shows considerable variation over the study area (Figure 3(iii)). The high latitude stations typified by Thorshavn and Tromso show no significant variation in cloud amount with season while more central northern European stations (e.g. Fano and Graz) show a clear drop in average cloudiness in the summertime. The more southerly stations exhibit this seasonal decrease much more clearly and Arta and Port-Said show a decrease in the range of cloud amount observed in the summer. It is also tempting to speculate on the reality of the apparent decrease in mean monthly cloud amount between the cold and warm period at Fano. Whilst few stations show a consistent enough alteration to affect the histograms in Figure 2 seasonal differences between the cold and warm periods could exist. Seasonal (i.e. three month groups) and annual trends and differences in cloud amount for the cold and warm periods identified by Lough *et al.* (1983) are analysed in the following two sections.

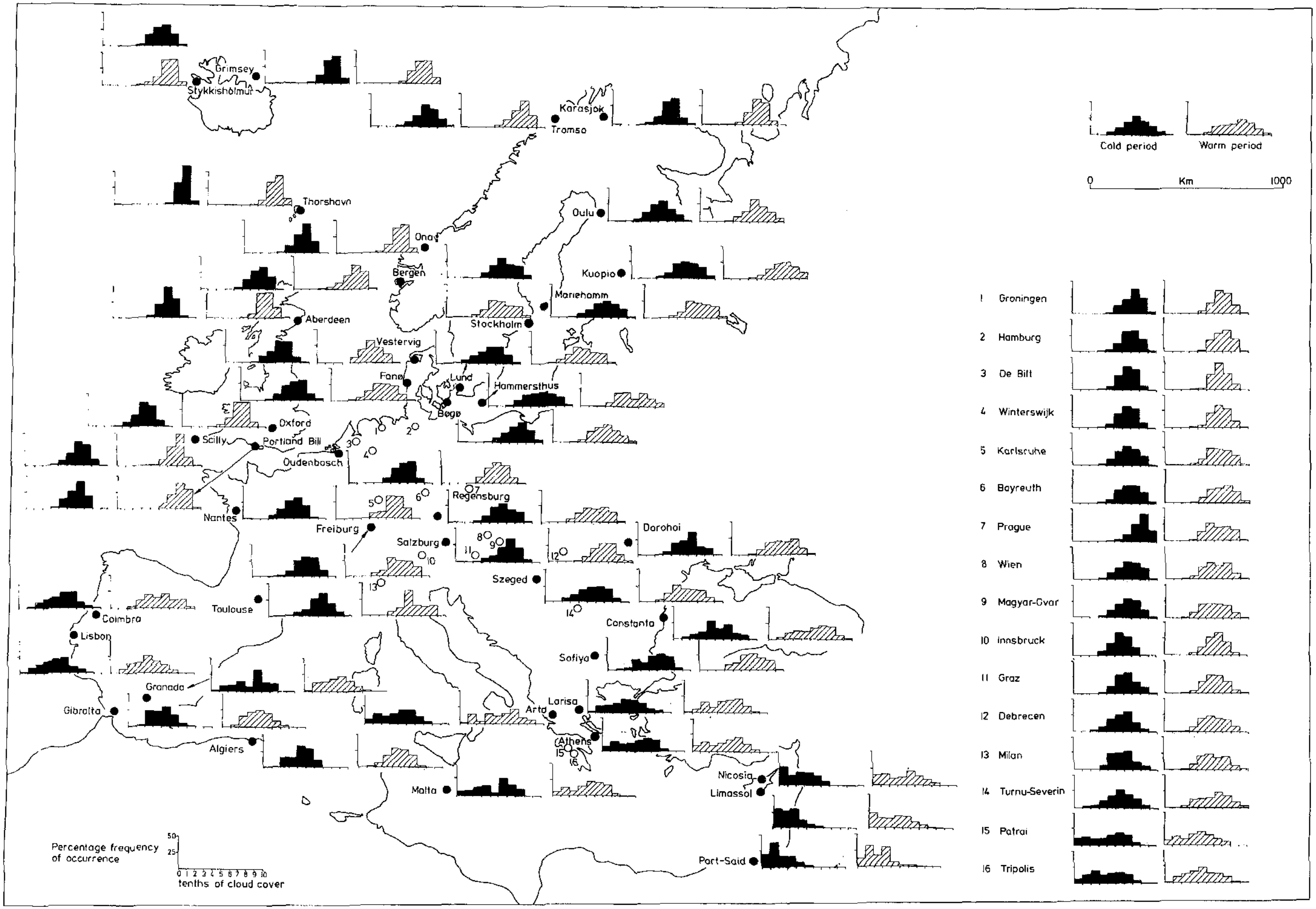


Fig. 2. Location of the 58 stations used in this study. The cloud characteristics are illustrated by a pair of histograms of percentage frequency of occurrence of mean monthly cloud amount for the cold and warm periods. Data for 42 stations are given *in situ* with the additional 16 stations being located by numbered points on the map.

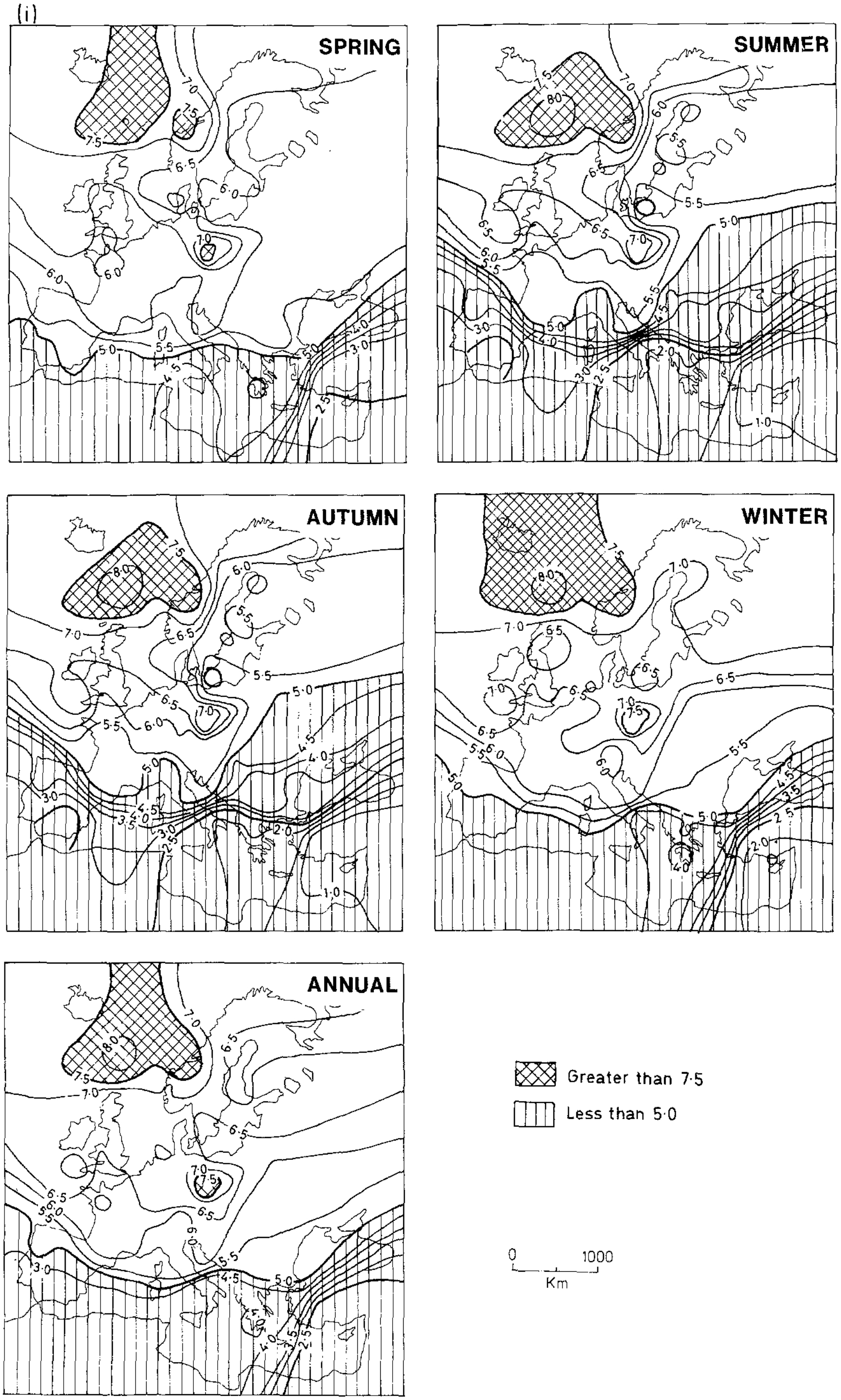
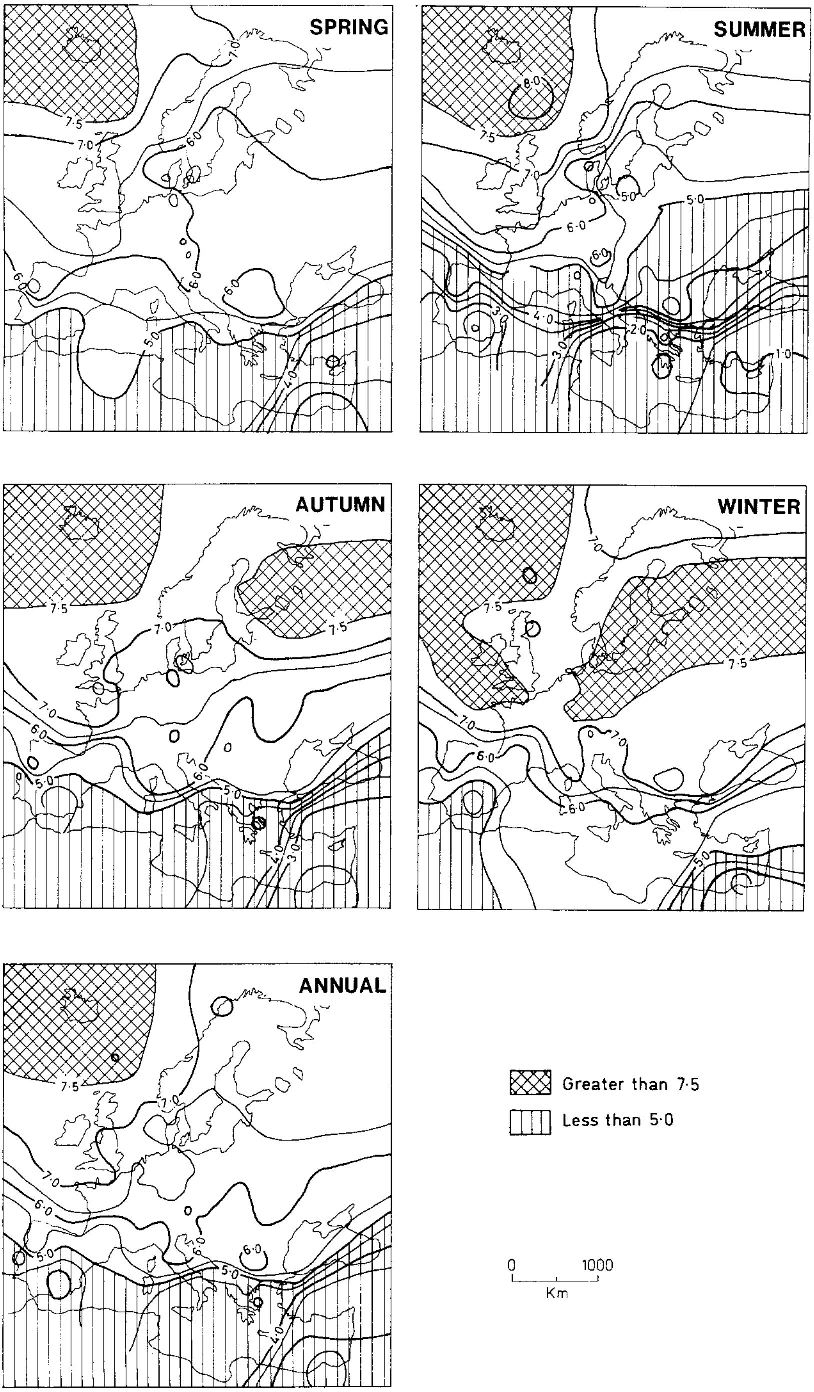
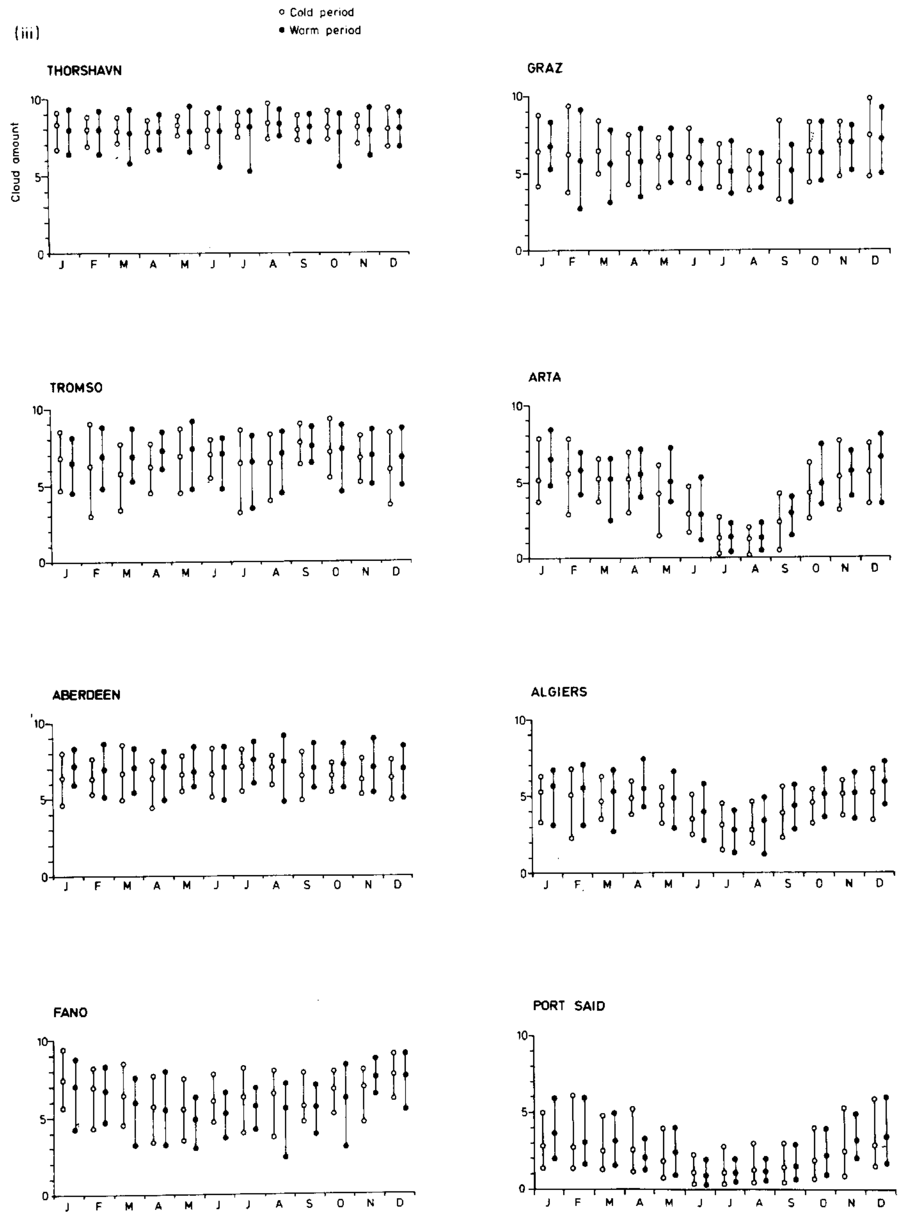


Fig. 3. (i). Mean cloud amount in tenths for the cold period for the annual and four seasonal values. (ii). As for (i) for the warm period. (iii). Scattergraphs for selected stations: Thorshavn, Tromso, Aberdeen, Fano, Graz, Arta, Algiers, Port-Said. Mean and extreme values of monthly cloud amount for both the cold and warm periods are plotted.

(ii)


SPRING
SUMMER
AUTUMN
WINTER
ANNUAL
7·5
7·0
6·0
5·0
4·0
3·0
2·0
1·0
8·0
0
Greater than 7·5
Less than 5·0
0
1000
Km



4. Changing Cloud in a Warming World

Before examining the mean difference in cloud amount between the cold and warm 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 medium term filtered trend has been computed so that any changes in variability would be decoupled from possible changes in mean values. In order to remove long time period (e.g. decadal) trends, a 1:2:1 binomial filter was applied to each of the 20 yr periods and the variances of the residuals from the filtered values analysed. This is the same methodology as employed by Lough *et al.* (1983). In order to retain a 20 yr filtered data set it was necessary to derive four more years' data: one at the beginning and end of each period analysed.

The F test was applied to establish, at a 1% significance level, which stations exhibited 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. Figure 4).

A few stations showed a significant change in cloud variability in the 'warming world'. In particular Thorshavn and Stockholm exhibited statistically significant differences in variability in the annual and 3 of the 4 seasonal cases. Other than these stations there were only a few (~5) which showed changed variability between the two periods in any one season and no other stations showed seasonal consistency in variability difference. All stations for which the F test failed at the 1% level were excluded from the maps shown in Figure 4. Overall there is little evidence of a change in variability in cloudiness for most of the European area analyzed in the warming world model. On the basis of this result the mean differences in cloud amount between the cold and warm periods have been analysed as a function of the standard deviation of cloudiness over the complete 40 yr (i.e., 1901–1920 plus 1934–1953) period.

The mean difference (cold minus warm) in cloud amount for the annual and four seasonal cases is shown in Figure 4. The mean difference at each station has been divided by the normalized 40 yr 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 show a similar degree of 'spottiness' as the precipitation differences for the same periods as computed by Lough *et al.* (1983) (Figure 5). This is partly the result of uneven spatial coverage by the station network used in the cloud analysis which is very much more limited than the temperature data set employed by Lough *et al.* (1983) which is a gridded data base for the northern hemisphere. It is also the result of the fact that cloudiness is less regionally coherent than, for example, mean sea-level pressure, being dependent upon local features such as orography. Despite this heterogeneity there is a tendency for the eastern and western sides of the region to show statistically significant increases in cloud amount while the more continental central area exhibits 'pockets' of statistically significant cloudiness decrease (i.e. positive differences in Figure 4). In particular cloud increases over Norway and Sweden, the U.K. and northern France and over the countries bordering the eastern Mediterranean. Cloud increases are also seen around the western edge of the Mediterranean although here there are fewer stations. The stations in France, Germany and other 'central' north-west European countries show a slight decrease in cloud amount particularly in March/April/May (spring) and June/July/August (summer), though this is less coherent and smaller in magnitude than the surrounding increases, being

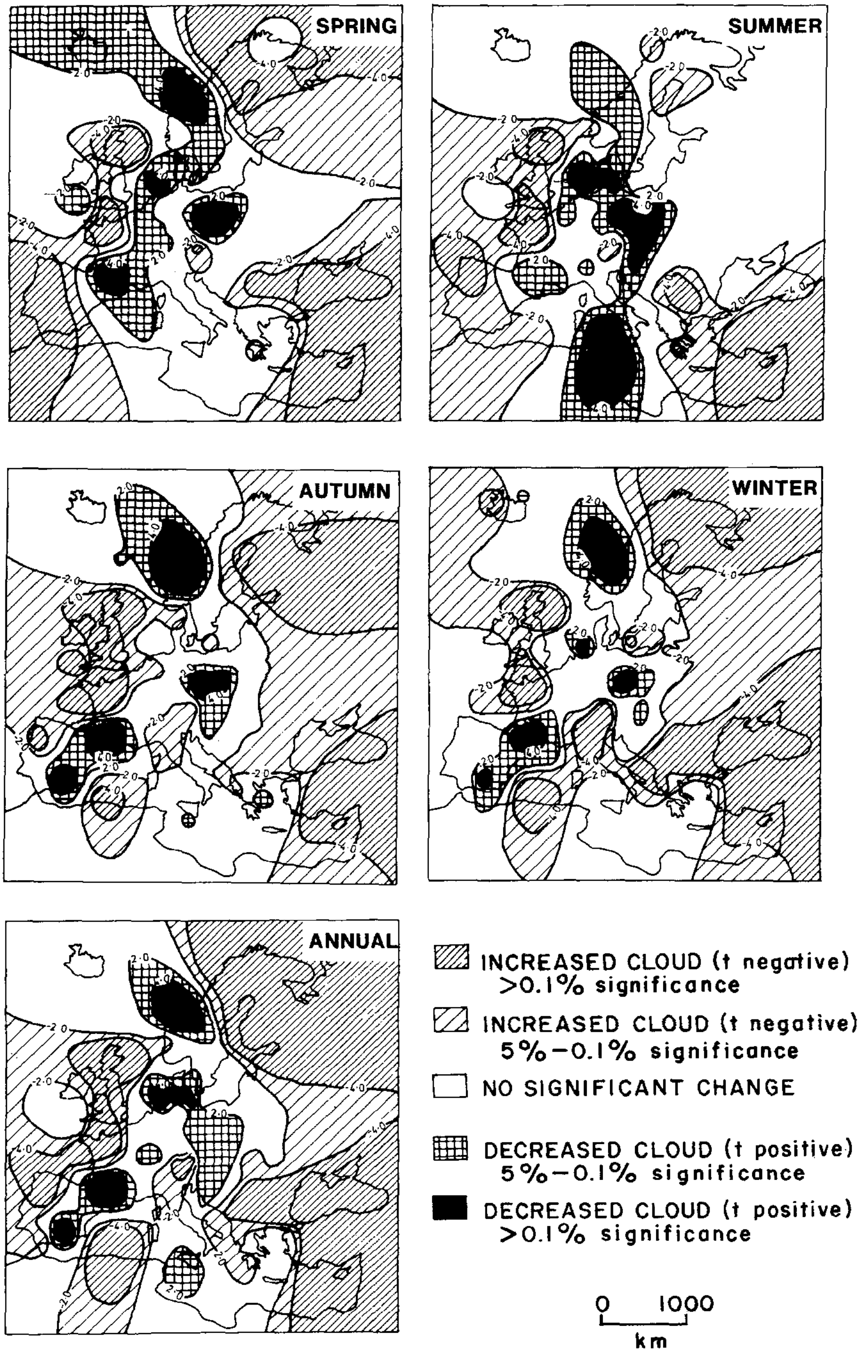


Fig. 4. Variation of the Student's t statistic generated from the mean differences (cold minus warm period) for the annual and seasonal cases. A negative difference (cold–warm) suggests an increase in cloudiness in a warmer world. The values at each station have been normalized by the station standard deviation for the 40 yr 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.

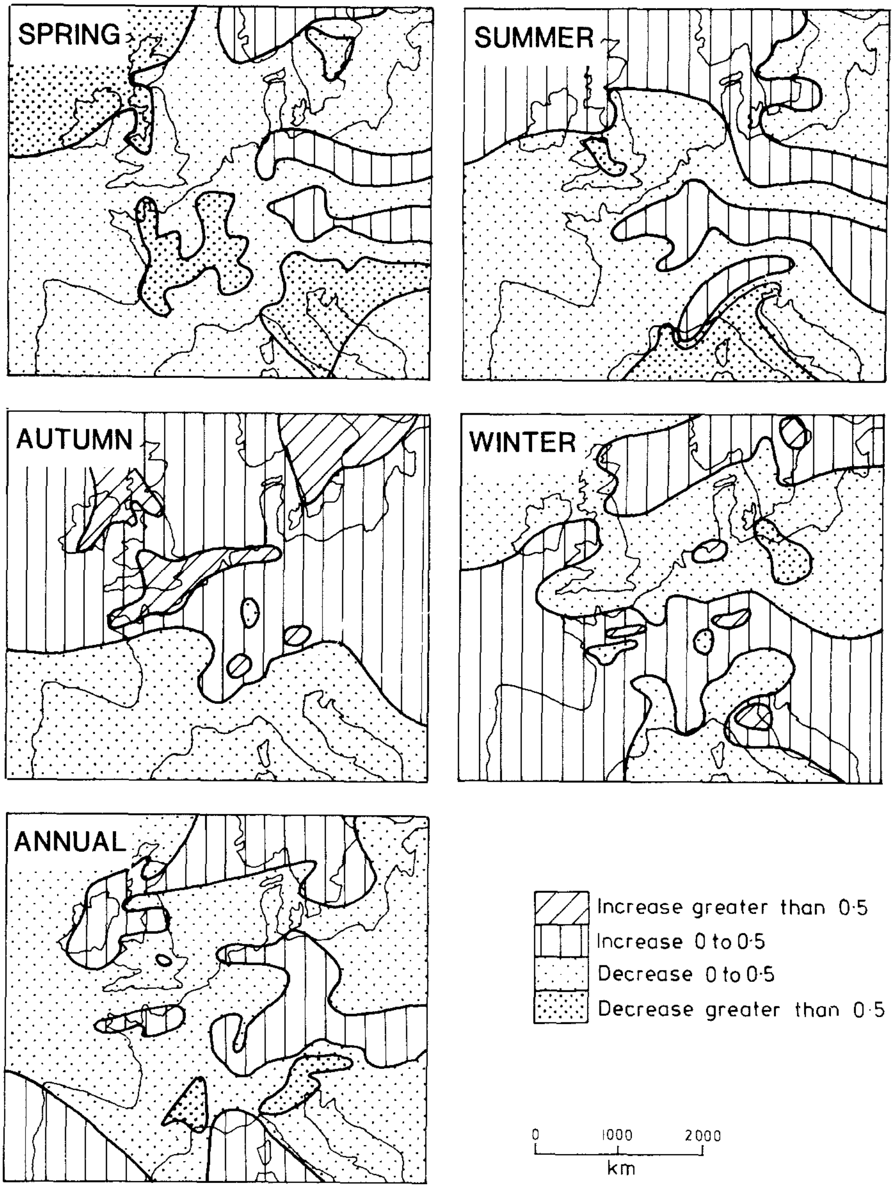


Fig. 5. Changes in precipitation (warm minus cold) shown in units of local standard deviation (after Lough *et al.*, 1983).

generally around the 5% level of statistical significance. In the autumn and winter seasons the central region of decreased cloudiness becomes still less coherent. In both these seasons the study area overall exhibits a statistically significant (at the 5% level) increase in cloud in the warm world analogue period.

Figure 4 suggests a tendency towards greater cloud amounts in a warmer Europe. This trend is most clear in maritime areas which could be because of their proximity to open water. Some modelling studies (e.g. Manabe and Wetherald, 1980; Washington and Meehl, 1984) support this finding and suggest that the increase in low cloud amount over or near maritime regions, caused by thermal forcing increasing local evaporation, might be more noticeable in middle to high latitudes where more stable conditions trap this moisture in the lower troposphere. Alternatively the cloud increases in the maritime fringes could be a coincidental result of the controlling pressure fields. Lough *et al.* (1983) point out that there was an increase in blocking situations in the warm period. Pressures were, on average, higher over continental north-west Europe but slightly lower to the north and south of the area. Cloud decreases over the central part of the study area are likely to be associated with the increase in anticyclonic activity. There seems to be little spatial coherence between the two parameters studied by Lough *et al.* (1983): temperature (Figure 1(b)) and precipitation (Figure 5) and cloudiness studied here (Figure 4). However, Lough *et al.* (1983) hypothesize that there was a reduction in sunshine hours in autumn over northern Europe which seems to be in agreement with the cloudiness increases over northern Europe shown in the September/October/November (autumn) map (Figure 4). They note that such a decrease in hours of sunshine could have an important effect in delaying the ripening of crops, despite the generally increased temperatures over Europe and lengthened growing season.

5. Modelling Seasonality as a Surrogate for Temporal Change

It has been suggested (Warren and Schneider, 1979) that a very powerful test of climate models is an analysis of how well they simulate the change in climatic characteristics between extreme seasons i.e. between summer and winter. Despite the fact that results of GCM studies are, as yet, difficult to relate precisely to geographical regions, it seems worthwhile to present the cloud differences between summer and winter in the two periods studied here. Figure 6 shows the mean cloud differences (December/January/February (winter) minus June/July/August (summer)) for the cold and warm periods. In each case the mean cloud difference has been divided by the normalized pooled standard deviation of the cloudiness for the two seasons for the 20 yr period. The contours are drawn in increments of normalized pooled station standard deviation. The contrast between Figure 4 and Figure 6 is apparent. The seasonal change in cloud amount in moving from cold (winter) to warm (summer) conditions is much more consistent. The maps in Figure 6 show a decrease in cloud amount in summer over almost the whole region. The seasonal change in cloud (Figure 6) is also greater at almost all locations than the change associated with moving from the cold to the warm period and is statistically significant at the 0.1% level everywhere except the north west corner. These results are not surprising since the seasonal temperature change is much greater at practically all locations. With the exception of two regions, cloud decreases over the whole of Europe. In the Mediterranean and southern Europe this change can be $>10\sigma$ and is $>5\sigma$ over most of the continent of Europe. The small area which shows an increase in cloud in the summer is typified by stations such as Tromso which, as can be seen in Figure 3 (iii), have considerable cloud all year round.

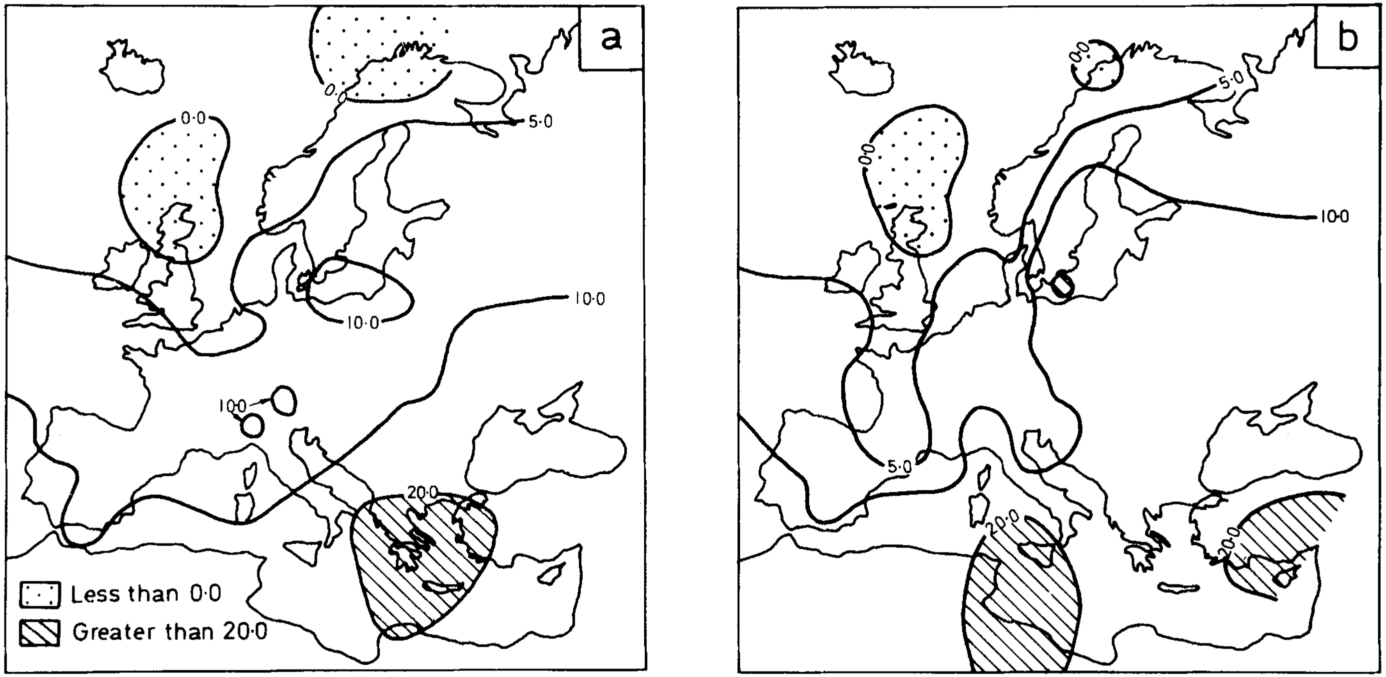


Fig. 6. (a). Normalized differences between the winter (DJF) and summer (JJA) seasons (i.e. DJF–JJA) for the cold period. The normalizing factor is the pooled standard deviation at each station divided by $\sqrt{[n_1 n_2/(n_1+n_2)]}$ where n_1 and n_2 are the number of valid data items for winter and summer within each 20 yr period. (b). As for (a) but for the warm period. [Contour values are of mean difference divided by the normalized standard deviation and are therefore directly comparable with the contour values in Figure 4].

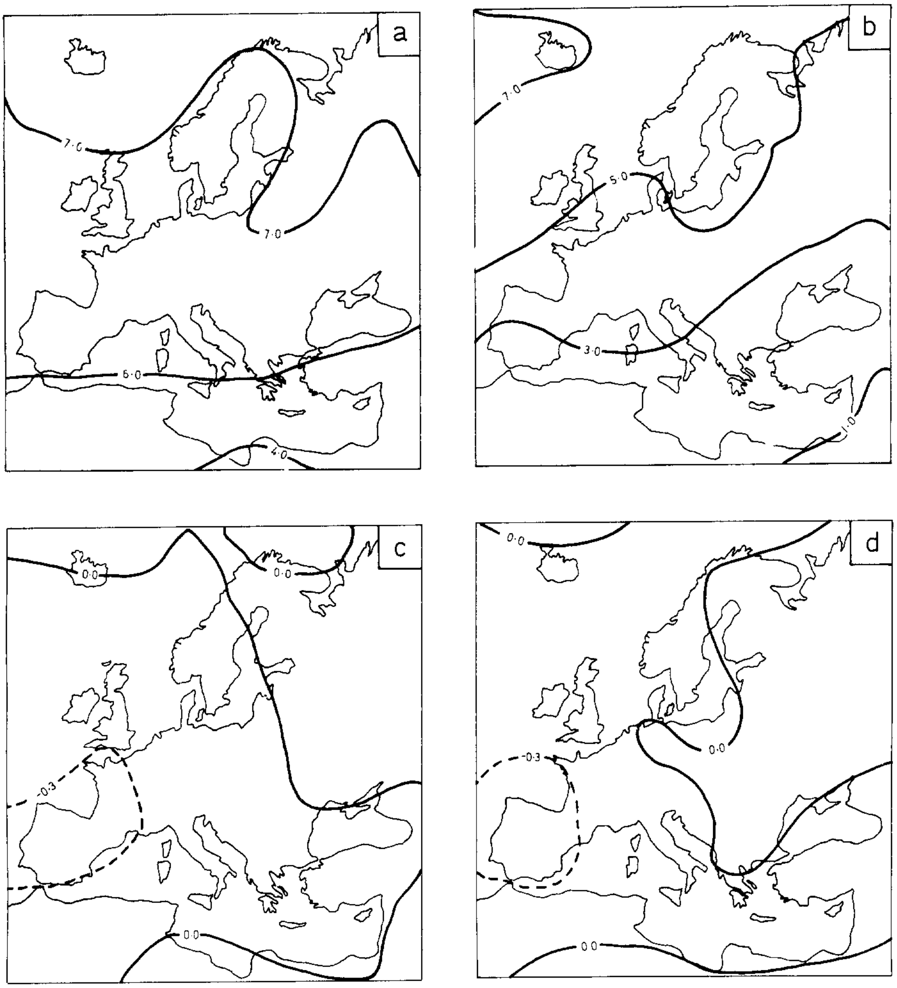


Fig. 7. (a)(b). Mean European cloud for January (a) and July (b) predicted by the standard version of the GISS GCM (after Hansen *et al.*, 1983). Five year average values of cloud amount are shown. (c). Differences between annual mean cloud and perturbed cloud for an experiment in which the solar constant was increased by 2% (after Hansen *et al.*, 1984). (d). Differences between annual mean cloud and perturbed cloud for an experiment in which the burden of atmospheric CO_2 was doubled (after Hansen *et al.*, 1984). (Negative contours are dashed in (c) and (d)).

While it is somewhat unfair to isolate a small region from sensitivity studies with a global GCM, Figure 7 has been taken from two recent publications describing results from the GISS GCM (Hansen *et al.*, 1983 and 1984). Figures 7(a) and 7(b) show the January and July cloud cover amount as predicted by the standard version of the GISS GCM. Cloud amounts are averaged from 5 yr of simulation. Figures 7(c) and 7(d) show cloud amount differences for two cases of climatic perturbation: Figure 7(c) is for a 2% increase in the solar constant and Figure 7(d) for doubled CO_2. These cloud differences can be compared with the observational data shown in Figures 3, 4 and 6. In the case of the seasonal change in cloudiness, the predictions of the GISS GCM seem to agree fairly well with the observational data, particularly when it is borne in mind that the observational data are for short (20-yr) periods only and the GISS GCM has a coarse spatial resolution ($8^\circ \times 10^\circ$) which hardly permits investigation of small regions such as Europe. In the case of increased CO_2, however, and also, incidentally, in the case of increasing the solar constant, both of which lead to increases in mean surface temperature, the GISS GCM predicts a *decrease* in total cloud amount over Europe of about 0.2 tenths. The warming world analogue model described here, in contrast, shows a general tendency towards *increased* cloud amount (Figures 3 and 4) which can be as large as ~1.5 tenths and is generally 0.2–0.4 tenths over the region. It must be noted that the GISS GCM results in Figure 7(d) relate to a doubled CO_2 experiment in which global mean temperatures rose by around 4 °C while the warming world analogue model is for a northern hemisphere temperature increase of 0.4 °C of which perhaps 0.2 °C can be attributed to CO_2. However, there is no obvious reason why more than an order of magnitude difference in the degree of warming should result in a change in the sign of the cloud changes predicted. Hence, the simulations of this GCM, at least, which suggest cloud amount decreases when moving from a cold to a warm situation (both seasonally and in a warming world), are corroborated by observations *only* for the seasonal case (and not for the warming world). This implies that it is insufficient to infer that a seasonally verified cloud prediction sheme in a GCM will be, *de facto*, appropriate in a warming world situation.

It is, of course, essential that cloud type (i.e. radiation parameters and cloud height) be predicted successfully as well as total cloudiness but observational data such as those described here offer little information about these other cloud characteristics. In addition it must be noted that the results presented here, although very tentative, seem to cast doubts upon the usefulness of the seasonality test for climate models, at least in the case of cloud prediction. A possible reason for this failure is the increasing importance of blocking activity in the analogue warming case which would be unlikely to occur in the seasonal transition and was probably poorly simulated in the numerical model study of increasing CO_2 or solar constant. If seasonal cloud differences such as those shown in Figure 6 could be produced on a larger, preferably global, scale, they might be of value for climate modellers since in attempting to improve cloud prediction schemes it would be worthwhile to evaluate the success of the parametrisation scheme in simulating the seasonal variation in total cloudiness. However, the results presented here suggest that historical data as well as seasonal data must be examined if the full extent of likely cloudiness changes is to be understood.

6. Conclusions

A warming world analogue model has been constructed for part of Europe in order to analyse cloud amount changes within the constraints of the availability of data. Whilst noting the possible weakness of the link between increasing atmospheric CO_2 and the temperature changes between the two periods studied it can be stated that the transition from the cold to the warm period seems to lead to an increase in total cloud amount over all but the central part of western Europe. This is perhaps a surprising result since earlier studies (e.g. Barrett, 1976) and the seasonal analysis described in Section 5 might lead to the hypothesis that increasing temperatures would tend to be associated with decreases in cloud amount.

It would be most unwise to try to extrapolate the results presented here for Europe into regional or global predictions. It seems likely that some of the increase in cloudiness which seems to dominate the transition from cold to warmer conditions may be the result of the increase in the frequency of blocking situations in the warmer period. Lough *et al.* (1983) note that annual mean sea level pressure is increased over most of Europe in the warm period as compared to the cold period whilst pressure is lowered over the eastern Mediterranean and to the north of Norway. Thus the increased cloud over the Mediterranean and the northern boundary of the study area could possibly be the result of increased frequency of passage of depression systems to the north or south of their usual path. While this explanation is not entirely satisfactory it could certainly be a contributory factor. The conclusions presented here therefore support the point made by Lough *et al.* (1983) that greater attention must be paid to the successful simulation of blocking situations in climate models, especially as cloud feedback effects would tend to act in a positive sense so as to enhance individual anticyclonic features and perhaps the frequency of their occurrence. A second, but much more tentative, reason for the increasing cloud amount, particularly in the southern part of Europe, could be an increase in convective activity, causing an increase in cirrus cloud amount developed in convective situations. Hansen *et al.* (1984) note that in their doubled CO_2 experiment a secondary cause of the positive feedback of cloud on surface temperature was the increase in cirrus cloud amount.

The comparison of the predictions of cloud changes simulated by the GISS GCM (Figure 7) and derived from the observational data analysed here (Figures 3 and 4) suggests that prediction of cloud cover, an essential feature of climate models cannot be fully tested by a seasonal comparison. Since the climate system sensitivity to cloud changes may be significant (e.g. Ohring *et al.*, 1981) more thorough methods of validating cloud prediction schemes should be sought.

The preliminary results presented here suggest that careful analysis of surface observations of cloud amount could contribute to the understanding of cloud-climate feedback effects *via* the historical analogue methodology. Larger-scale analyses such as these could prove to be a useful tool for improving climate model cloud prediction schemes. In addition if satisfactory data can be found cloud type/height information would prove most interesting.

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