Simultaneous Occurrence of Different Cloud Types

STEPHEN G. WARREN,*,@ CAROLE J. HAHN@ AND JULIUS LONDON†

*Dept. of Atmospheric Sciences, University of Washingon, Seattle, WA 98195; @Cooperative Institute for Research in Environmental Sciences, University of Colorado, Boulder, CO 80309; and †Dept. of Astrophysical, Planetary and Atmospheric Sciences, University of Colorado, Boulder, CO 80309

(Manuscript received 19 September 1984, in final form 13 February 1985)

ABSTRACT

Cloud observations from land stations and from ships in the ocean are used to investigate the frequency of observation and the co-occurrence of different cloud types, and the geographical and seasonal variations of these co-occurrences. Ground-based observations are used because they provide a more definitive identification of clouds by type than do satellite observations. The clouds are grouped into six types (cirrus + cirrostratus + cirrocumulus, altostratus + altocumulus, stratus + stratocumulus, nimbostratus, cumulus, and cumulonimbus). The results are expressed as frequency of occurrence of different cloud types and as contingency probabilities; that is, given that one cloud type is present, the probability that another particular type is also present is computed. Several sources of bias are identified, and their effects on the results are estimated.

It is found that, on the average at all latitudes and in all seasons, clear skies occur more frequently, by a factor of about 4, over land than over the oceans; cumulus occurs twice as frequently over the oceans than over land but cirrus is reported with a somewhat higher frequency over land.

In general, cirrus and altostratus tend to occur together but altostratus and cumulus do not. The probability of co-occurrence of cirrus and cumulonimbus is much higher in the tropics 30°S–30°N than at mid- to subpolar latitudes. When cirrus or altostratus occurs over land, it is much more likely to be alone than when it occurs over ocean. Some of the reasons for these variations are discussed.

1. Introduction

Clouds are an important component of the earth's climate system. They affect the earth's radiation budget in both the solar and terrestrial radiation spectra. In turn, formation and dissipation of clouds are affected by the radiation and moisture fluxes in the atmosphere. The clouds vary in the geometric form, height, horizontal and vertical extent, phase (liquid or ice), and water content. They can therefore usually be classified into a small number of defined cloud types. To understand cloud physical processes and the climatic effects of clouds on radiation and precipitation, a climatological description of the geographical and seasonal distribution not only of total cloud cover, but also of individual cloud types, would therefore be useful.

It is common for two or more cloud types to occur simultaneously over the same location but at different levels in the atmosphere. The effects of individual clouds on the surface and atmospheric radiation budgets depend on whether other clouds are also present above or below them. A description of the co-occurrence of different cloud types could therefore aid the radiation calculations of climate prediction models and also help evaluate the schemes for generating clouds in those models. It could also assist in the comparison of cloud observations from the surface with those from satellites.

The reporting of cloud co-occurrences is complicated by the fact that overlapping layers may cause the upper clouds to be hidden from the view of a ground observer, and lower clouds to be hidden from the view of the satellite, a problem which is addressed in this study.

This study investigates the tendencies of various cloud types to occur together or to be mutually exclusive. Ground-based observations, rather than satellite observations, were chosen for the study because ground observers, being closer to the clouds, can resolve individual clouds within their field of view and thus can readily identify clouds by type. Satellite cloud type identification is still in a state of development, especially regarding the detection of clouds smaller than the satellite's resolution, typically a few km. Indeed, a major purpose of this study is to provide a reference data set to aid the development of satellite cloud-type identification methods for the International Satellite Cloud Climatology Project (ISCCP).

Our analysis here is restricted to frequency of occurrence of the different cloud types and the probabilities, given one cloud type, that another particular type is also present. As such it is the first step in our development of a ground-based climatology of the average fractional amounts of the cloud types by season and geographical location. The fractional cloud type amounts can be obtained as the product of frequency-of-occurrence (fraction of weather observations in which a cloud of this type is reported present, given that it is possible to see whether it is present), and amount-when-present (the average fraction of the sky which is covered by this cloud type, given that it is present). For example, if cumulus is reported present in 30% of the weather observations from a station, and if it covers an average of 40% of the sky when it is present, then the average amount of cumulus at that station is 12%. The present study is an investigation of the first of these two components and of the biases which can affect is accuracy. This study, therefore, does not provide any direct information about cloud amounts. Furthermore, if the field of view is increased, the frequency of occurrence of a cloud type increases while the amount-when-present decreases. The values obtained here for frequency and for co-occurrence probabilities apply only to an area the size of the ground observer's field of view, which is larger for high clouds than for low clouds. For an unobstructed horizon, the radius of view can be as large as 160 km for clouds at 2 km above the surface, and 360 km for clouds at 10 km. Quantitative comparison with satellite observations based on a different field of view should only be made on average cloud amount, a quantity which should be independent of field of view. Only limited qualitative information can result from comparing cloud frequencies (e.g., Woodbury and McCormick, 1983). The frequencies we discuss here are therefore regarded as intermediate quantities for the computation of cloud amounts. The co-occurrence probabilities, however, should be representative of an individual meteorological condition because they apply to the area included in the ground observer's field of view.

Detailed results of this study are reported in two atlases (Hahn *et al.*, 1982, 1984): one for the oceans at 15° latitude × 30° longitude resolution, and one for the land areas at 5° × 5° resolution [While 15° × 30° resolution is adequate over large portions of the ocean, 5° × 5° would have been desirable to give better resolution in longitude along north–south coasts and to give better resolution of latitudinal variations. However, although there are sufficient ship observations to compute frequency of occurrence and average cloud amounts over the ocean at 5° × 5° (in preparation), there are not enough to provide reliable values of cloud-type co-occurrences at that resolution, so the 15° × 30° resolution was used for the present study.] The atlases contain maps, for each of four seasons, of the frequency of occurrence of each cloud type, of clear sky, and of fog, and maps of the co-occurrence probabilities of various combinations of cloud types. Here we present zonal average values of the co-occurrence probabilities and examine contrasts between land and ocean.

2. Data source

The sole source of data is individual synoptic weather observations made routinely on land at weather stations and in the ocean by observers on merchant ships, military ships and weather ships (predominantly merchant ships), as reported in the standard form of the WMO synoptic code (WMO, 1974). The information on clouds in these reports consists of total cloud amount (N), lower cloud amount (N_h), low cloud type (C_L), middle cloud type (C_M), high cloud type (C_H), present weather (ww), and base height of the lowest cloud (h). If information was lacking in a particular category, a slash was recorded by the observer.

The analysis for the oceans used about 10 million observations from the period 1965–76, which were the years of most complete global coverage in the Consolidated Data Set (Caton, 1978) of the U.S. Navy Fleet Numerical Oceanography Center (FNOC). The land data archive was also obtained from FNOC, and consists of about 100 million observations covering the 10-year period 1971–80. The two sources therefore do not represent the same years. All observations within a meteorological season were weighted equally, irrespective of year.

The reports, both on ships and on land, are generally made every six hours: at 0000, 0600, 1200, and 1800 GMT. About 15% of the ships and 70% of the land stations report observations also at the intermediate three-hourly times. Observations in the ocean in the early years showed no day-night sampling bias, but in the later years there was a tendency for more observations in the daytime. Daytime observations contributed 50% of the total in 1965, but rose to 62% in 1976. About 20% of the land stations make observations only in daytime.

3. Method of analysis

The cloud types defined in the synoptic code were grouped into six classes for this study: 1) cirrus + cirrostratus + cirrocumulus (Ci), 2) altostratus + altocumulus (As), 3) cumulonimbus (Cb), 4) cumulus (Cu), 5) nimbostratus (Ns) and 6) stratus + stratocumulus (St). The assignment procedure for grouping the cloud types of the synoptic code into these six classes is discussed in the two atlases referred to before (Hahn *et al.*, 1982, 1984). There is no single code number in the synoptic code which always means Ns. Whenever one of the codes appeared which could possibly mean Ns, we designated that cloud as Ns only if rain or snow was actually falling at the time of observation.

Computation of the co-occurrence probability of a low cloud with a higher cloud must account for the fact that higher clouds are only visible when the lower clouds are not overcast. In this study a simple assumption was used, namely that the probability $P(L \Rightarrow U)$ of an upper cloud U, given a lower cloud L, is assumed to be the same when U cannot be seen (because L is overcast) as when it can be seen (when L is present but not overcast). The translation of this assumption into the detailed logic of the procedure is given by Hahn *et al.* (1982).

4. Biases

A number of biases can affect the results of analyzing ground-based observations for a cloud climatology. Some of these biases affect the frequencies and co-occurrence probabilities much more severely than they would affect the fractional cloud type amounts.

Cloud observations from transient ships are subject to biases due to the use of untrained observers (observer bias), the possible attempt of ships to avoid storms (fairweather bias), and a tendency for some ships to travel in groups (convoy bias). Also, observers may neglect to take observations when visibility is poor (fog or Ns) because they cannot take time away from navigation. These biases have been discussed by Bunker (1976) and Quayle (1980), who compared observations from transient ships to those of nearby weatherships (all in northern midlatitudes). We have taken the data source described by Quayle (1980) and determined the bias in total cloud cover, finding that cloud cover reports of stationary weather ships on average exceed those of nearby transient ships (within 1° of latitude and longitude) by about 2% (e.g., transients might report an average cloud cover of 60% while the nearby weather ship reports 62%). Because the bias in total cloud cover is rather small, and since biases in the frequency of different cloud types would be likely to vary geographically, we did not attempt to correct for these three sources of bias. They apply specifically to the ocean observations, but the remaining biases to be discussed apply to both land and ocean.

The bias with probably the greatest influence on our results is the tendency of ground observers not to detect cirrus and altostratus when they are present at night, the "night detection bias," suggested by Riehl (1947). We find in the oceans that frequency of occurrence of cirrus, f(Ci), in the daytime averages about 1.3 times the diurnal-mean value. Because f(Ci) does not vary smoothly with time of day but instead shows a sharp increase at sunrise and decrease at sunset, we think that the diurnal variation is at least partly due to a night-detection bias rather than a true variation. The same pattern, but with only about half the amplitude, is found for As/Ac. Since both co-occurrence atlases were prepared with the use of all observations, it is suggested that the frequency of occurrence of cirrus and of As/Ac should in general be increased by factors of up to 1.3, but with some geographical variation. Application of such a correction factor would, however, involve the assumption that the diurnal variations of f(Ci) and f(As) in the observations is due entirely to the observer bias, whereas part of it maybe a true diurnal variation of the clouds. (The true diurnal variation could of course be opposite to the diurnal variation of the bias, requiring an even larger correction factor). Such a correction factor, if applied to f(Ci) and f(As), would also be applied to all probabilities of co-occurrence of these two types contingent on the presence of other clouds: $P(X \Rightarrow \text{Ci})$ and $P(X \Rightarrow \text{As})$. Ground-based lidar and infrared satellite observations could provide information to help estimate this possible day/night bias in the ground-based Ci and As reports.

Another important bias is the underestimation of frequency of upper clouds due to the possibility that an upper cloud is present behind a partial lower cloud cover yet reported absent because it does not intrude into the region of the sky which is visible through the lower layer. This "partial-undercast bias" results in a systematic underestimate of the frequencies of upper clouds Ci and As (but correspondingly leads to an overestimate in amount-when-present of those clouds so that amount would be unbiased). The effect of this bias on f(Ci) is greatest when a low stratus cloud layer is nearly unbroken. It has not been quantified, but its effects can be seen in Fig. 1b of the ocean atlas.

5. Zonal average frequencies and co-occurrence probabilities

Tables 1a–d give zonal average values of the frequencies and co-occurrence probabilities for four broad latitude zones covering most of the earth. Two numbers are given for each entry in Table 1: the land value on the left and the ocean value on the right. Each zonal average probability in Table 1 is given for four seasons as noted to the right of the table. The columns in the tables give the probability of occurrence of a given cloud type under different circumstances, i.e., together with specified other clouds. Also shown in the last column are the probabilities $P(A \Rightarrow \text{NO})$, i.e., given cloud type A, the probability that no other cloud type is present. Certain elements of the table are blank simply due to the definitions of cloud types. Only one low cloud type C_L is reported in a single observation, so our analysis causes the co-occurrence probabilities of Cu, St and Cb with each other to be zero by definition.

Contingency probabilities were computed for 15° latitude × 30° longitude boxes over ocean and 5° × 5° boxes over land (but with coarser longitude-resolution at high latitude over land). For an individual box over the ocean the data-sampling requirement

TABLE 1a. 30°–60°N land/ocean average contingency probabilities (percent).*

Given cloud type	Frequency of occurrence (f)	Probability that these are also present							Season**
		Ci	As	Ns	Cu	St	Cb	NO	
Ci	47/27	—	32/67	12/16	4/20	20/49	3/9	55/10	DJF
	50/33	—	33/62	6/12	11/19	19/45	7/6	48/17	MAM
	42/37	—	41/63	4/9	20/21	19/45	13/7	31/16	JJA
	41/31	—	37/66	9/11	9/26	22/44	6/9	45/11	SON
As	30/42	54/43	—	1/1	5/19	34/62	4/10	30/8	DJF
	31/45	56/46	—	0/1	10/18	31/61	9/8	24/10	MAM
	35/47	49/49	—	0/1	17/19	26/61	16/8	25/10	JJA
	32/44	49/46	—	0/1	10/23	34/56	8/10	28/8	SON
Ns	12/13	56/34	2/7	—	1/2	49/58	2/2	7/4	DJF
	8/10	—/40	2/6	—	2/1	57/59	5/3	4/2	MAM
	6/8	—/43	2/6	—	3/2	64/58	9/2	2/2	JJA
	9/9	—/40	2/7	—	1/2	60/60	4/3	3/3	SON
Cu	5/22	48/25	31/36	2/1	—	—	—	38/53	DJF
	12/21	48/30	25/38	1/1	—	—	—	41/48	MAM
	19/22	43/36	29/42	1/1	—	—	—	43/43	JJA
	9/27	41/29	31/38	1/1	—	—	—	43/50	SON
St	30/57	38/25	36/50	22/15	—	—	—	25/30	DJF
	27/55	40/29	39/53	17/13	—	—	—	27/28	MAM
	24/54	37/33	41/57	12/10	—	—	—	33/26	JJA
	31/51	33/28	39/52	17/12	—	—	—	31/30	SON
Cb	5/8	41/28	39/49	6/3	—	—	—	33/41	DJF
	8/6	51/32	42/54	3/3	—	—	—	28/35	MAM
	12/6	51/42	49/61	2/3	—	—	—	26/26	JJA
	7/8	43/35	46/55	4/3	—	—	—	31/34	SON
Clear sky	25/5								DJF
	21/7								MAM
	22/8								JJA
	26/6								SON
Sky obscured due to fog	1/1								DJF
	1/3								MAM
	1/8								JJA
	1/2								SON

* "Ci" = Ci + Cs + Cc.
"As" = As + Ac.
"St" = St + Sc.
"NO" = no other cloud.
Left-hand numbers are for land; right-hand numbers for oceans.
** First letter of each month of 3-month season.

was as follows: of the times that A was present, we required that in at least 50 individual observations it was possible to see whether B was also present. For the land, we required 200 observations. Most boxes contain far more than the minimum number of observations. In particular, land boxes normally have either very large numbers of observations (because the box contains one or more stations) or else no observations at all. Thus the requirement of a minimum of 200 observations for an individual land box placed little restriction on the number of land boxes represented in the analysis. However, since for computation of $P(A \Rightarrow B)$, A must be present and the level of B must be visible, probabilities involving clouds A of low frequency, such as Cb in some locations, or clouds B not visible, such as high clouds over Ns, will in some locations not be computed (e.g., Cb $\Rightarrow$ Ci; Ns $\Rightarrow$ Ci).

The values in Tables 1a–d are averages of all boxes in the zone which satisfied the data-sampling requirement for individual boxes. A zonal average was not computed if values were available for less than one-third of the possible boxes, resulting in some missing entries in the tables, particularly for the probabilities contingent on nimbostratus.

Table 2 summarizes the results giving only two numbers for each probability: the average for the entire land area of the earth, and the average for the entire ocean area. These "global annual averages" were obtained as follows. For a particular co-occurrence probability in a season, the values from all boxes which satisfied the data-sampling requirement

TABLE 1b. 0°–30°N land/ocean average contingency probabilities (percent).

Given cloud type	Frequency of occurrence (f)	Probability that these are also present							Season
		Ci	As	Ns	Cu	St	Cb	NO	
Ci	42/27	—	31/66	2/4	16/42	19/31	5/13	49/9	DJF
	48/32	—	37/63	2/3	18/44	19/27	13/15	39/10	MAM
	49/39	—	48/68	4/4	20/42	25/27	19/20	24/6	JJA
	46/36	—	41/68	3/4	19/44	21/26	16/20	33/5	SON
As	28/39	48/45	—	0/0	17/37	29/39	7/15	26/7	DJF
	35/40	53/50	—	0/0	18/39	26/36	15/16	23/7	MAM
	48/49	51/54	—	0/1	19/37	31/35	19/20	20/5	JJA
	39/45	50/53	—	0/1	19/39	29/34	17/20	22/4	SON
Ns	6/4	—/37	—/13	—	—/3	—/64	—/5	—/5	DJF
	6/3	—/44	3/13	—	5/3	65/62	18/6	—/4	MAM
	7/4	—/45	4/15	—	5/4	66/59	17/7	—/5	JJA
	5/4	—/42	3/14	—	5/4	68/60	14/7	—/5	SON
Cu	21/45	39/26	31/33	0/0	—	—	—	44/56	DJF
	21/47	47/30	35/34	0/0	—	—	—	36/52	MAM
	22/44	53/38	47/41	1/0	—	—	—	27/43	JJA
	21/47	46/34	39/38	1/0	—	—	—	36/47	SON
St	26/30	36/29	45/54	6/8	—	—	—	34/34	DJF
	24/28	46/32	51/54	6/7	—	—	—	27/33	MAM
	33/30	50/36	60/60	9/10	—	—	—	19/27	JJA
	25/28	45/35	54/58	7/10	—	—	—	25/29	SON
Cb	6/10	57/35	56/55	4/1	—	—	—	20/35	DJF
	13/12	64/42	56/56	3/1	—	—	—	16/32	MAM
	20/16	66/49	63/61	4/2	—	—	—	11/26	JJA
	16/15	64/46	59/60	3/2	—	—	—	14/28	SON
Clear sky	29/9								DJF
	24/8								MAM
	19/4								JJA
	24/5								SON
Sky obscured due to fog	0/0								DJF
	0/0								MAM
	0/0								JJA
	0/0								SON

were averaged. The four global-average seasonal values were then averaged to obtain the annual average given in Table 2. These are therefore not true area-weighted global averages but instead the averages of the values in those boxes which had sufficient observations to meet the criteria described above. The "global average" probabilities contingent on Ns, for example, are therefore weighted toward the values for the regions where Ns is common.

The contingency probabilities may be compared with the average overall frequency of occurrence of each cloud type (leftmost column in all tables). The overall frequency of occurrence f of a cloud type is simply the number of times that particular type was reported present, divided by the number of synoptic weather reports which contained information about that cloud level (i.e., in which that level was not coded with a slash). That is, f is the fraction of times that the cloud type was reported present, given that it was possible to see whether it was present. The percentage of reports contributing to statistics of the middle and high levels are less than 100%, as shown in the second column of Table 2, because of occasional lower overcast.

Zonal average frequencies of occurrence are plotted in Fig. 1 as the average of all four seasons, for the six cloud types as well as clear sky and fog. (The lowest two frames use a vertical scale which is expanded relative to the upper four frames). Figure 1 shows that cirrus is reported much more frequently over land than ocean, except at the latitudes of the descending branches of the Hadley cells, around 25°N and 25°S. The peak in cirrus observations is found north of the equator, close to the mean latitude of the ITCZ, and is present in both ocean and land regions but much more pronounced over land. As/Ac, by contrast, is reported in the annual average more frequently over ocean than over land, except near the equator.

Cumulus and St/Sc are also observed much more frequently over the ocean than over land, probably because of the proximity to a water source, but the

TABLE 1c. 0°–30°S land/ocean average contingency probabilities (percent).

Given cloud type	Frequency of occurrence (f)	Probability that these are also present: Ci	As	Ns	Cu	St	Cb	NO	Season
Ci	49/33	—	52/65	4/4	29/45	31/28	15/18	16/4	DJF
	40/31	—	46/63	4/3	28/47	27/26	12/19	23/5	MAM
	26/22	—	33/65	2/3	22/41	22/33	4/16	43/7	JJA
	36/25	—	43/66	3/3	27/42	24/34	11/15	28/6	SON
As	51/43	49/48	—	0/0	24/39	39/36	15/19	16/5	DJF
	44/40	44/47	—	0/0	24/40	37/34	12/20	21/5	MAM
	30/38	29/37	—	0/0	20/35	35/42	5/17	35/6	JJA
	38/41	40/40	—	0/0	23/36	35/42	12/16	25/6	SON
Ns	6/4	—/—	4/14	—	6/3	73/65	8/6	—/3	DJF
	4/4	—/—	4/14	—	6/4	74/62	8/7	—/4	MAM
	4/3	—/—	—/15	—	—/2	—/68	—/5	—/5	JJA
	4/3	—/—	—/14	—	—/3	—/68	—/6	—/4	SON
Cu	29/48	48/31	43/36	1/0	—	—	—	31/50	DJF
	28/49	40/29	37/33	1/0	—	—	—	40/53	MAM
	22/45	24/21	27/31	0/0	—	—	—	58/60	JJA
	27/45	36/24	33/33	0/0	—	—	—	45/55	SON
St	35/30	44/31	59/55	11/10	—	—	—	20/31	DJF
	31/28	37/30	54/53	9/10	—	—	—	26/33	MAM
	27/35	24/22	43/50	6/8	—	—	—	42/38	JJA
	28/36	34/25	51/52	7/8	—	—	—	32/35	SON
Cb	15/14	58/41	62/58	3/2	—	—	—	18/30	DJF
	12/15	54/39	60/55	3/1	—	—	—	19/32	MAM
	7/12	—/29	—/54	—/1	—	—	—	—/37	JJA
	10/11	52/32	60/56	3/1	—	—	—	21/34	SON
Clear sky	10/4								DJF
	16/4								MAM
	34/5								JJA
	21/5								SON
Sky obscured due to fog	0/0								DJF
	0/0								MAM
	1/0								JJA
	0/0								SON

precipitating clouds Ns and Cb are about equally frequent over land as over ocean. St/Sc is the most commonly observed cloud overall. The low stratiform clouds St/Sc and Ns tend to increase in frequency toward the poles, whereas the frequency of cumulus decreases poleward. For example, nimbostratus is quite rare in the tropics but approaches 20% frequency north of 60°N. At high latitudes, cumulonimbus is rare over the land but relatively common over the ocean, indicating convective activity probably enhanced in regions where cold air is advected over warm ocean currents. The high values and broad maximum of observed cumulus frequency in equatorial and subtropical latitudes over the oceans of both hemispheres represent the persistent occurrence of "trade cumulus" in these regions.

Although the frequency maximum of cumulonimbus shown in Fig. 1 seems to be between 0° and 10°N over both land and ocean, more detailed analysis shows that the maximum of Cb over land is about 5 degrees north of the oceanic maximum, in agreement with Figs. 10.3 and 10.4 of Riehl (1978) showing the ITCZ on average farther north over land than over ocean.

A dramatic difference between land and ocean is seen in the frequency of completely clear sky (lowest left frame in Fig. 1). Maxima of f (clear) are found in the subtropics for both land and ocean as expected. The values are much higher over land at all latitudes, but especially in the subtropics. There is also a large seasonal variation of the frequency of clear sky which is not shown in this annual-average plot. Tables 1b and c show that in the subtropics a maximum is observed during the winter and spring of each hemisphere. The zonal average frequency of fog is low except in the mid-to-high-latitudes over the ocean, but fog is common in certain regions (20% in the Sea of Okhotsk in summer).

The averaging of all four seasons in Fig. 1 obscures the large seasonal variations which can occur in these

TABLE 1d. 30°–60°S land/ocean average contingency probabilities (percent).

Given cloud type	Frequency of occurrence (f)	Probability that these are also present: Ci	As	Ns	Cu	St	Cb	NO	Season
Ci	36/31	—	40/62	5/—	16/24	27/41	6/7	35/12	DJF
	37/31	—	42/64	5/—	11/23	28/43	3/9	38/12	MAM
	36/26	—	42/65	6/—	8/21	28/44	3/13	40/12	JJA
	38/31	—	41/63	4/—	14/21	26/44	4/8	38/15	SON
As	32/47	46/43	—	0/0	15/23	35/56	9/8	28/11	DJF
	34/45	48/45	—	0/1	11/21	39/55	5/10	29/11	MAM
	35/40	45/42	—	0/1	9/18	39/56	4/14	32/10	JJA
	33/46	49/42	—	0/1	13/19	37/59	6/11	28/10	SON
Ns	5/11	—/—	3/6	—	3/1	67/59	5/2	2/1	DJF
	6/11	—/—	3/9	—	2/1	67/61	3/2	3/2	MAM
	8/8	—/—	2/13	—	2/1	66/64	2/3	3/4	JJA
	6/9	—/—	3/11	—	3/1	67/69	4/2	3/2	SON
Cu	17/26	35/28	27/40	1/1	—	—	—	51/47	DJF
	12/26	33/26	28/37	1/1	—	—	—	52/52	MAM
	10/25	30/22	28/32	1/0	—	—	—	54/58	JJA
	15/24	34/26	27/38	1/0	—	—	—	52/50	SON
St	33/54	31/27	35/51	10/13	—	—	—	42/29	DJF
	36/54	30/29	37/49	11/15	—	—	—	40/29	MAM
	39/54	27/26	37/46	14/14	—	—	—	40/33	JJA
	35/56	30/26	37/51	11/13	—	—	—	40/28	SON
Cb	7/7	41/33	48/55	3/2	—	—	—	34/34	DJF
	4/10	38/31	50/52	4/2	—	—	—	34/37	MAM
	4/13	34/26	48/46	5/2	—	—	—	35/43	JJA
	5/9	40/31	49/55	4/2	—	—	—	34/35	SON
Clear sky	23/4								DJF
	23/4								MAM
	22/6								JJA
	21/4								SON
Sky obscured due to fog	0/3								DJF
	1/2								MAM
	1/2								JJA
	0/2								SON

TABLE 2. Global average contingency probabilities (percent).

Given cloud type	Frequency of occurrence (f)	Fraction of reports contributing to statistics of type	Probability that these are also present: Ci	As	Ns	Cu	St	Cb	NO	
Ci	44	73	—	38	6	16	22	9	39	land
	31	65	—	64	6	34	35	14	9	ocean
As	36	87	49	—	0	14	32	11	27	land
	43	74	46	—	1	29	47	14	8	ocean
Ns	9	97	58	3	—	2	60	6	5	land
	7	96	41	12	—	2	62	5	4	ocean
Cu	17	100	44	33	1	—	—	—	40	land
	37	100	29	36	0	—	—	—	50	ocean
St	30	100	38	45	14	—	—	—	29	land
	42	100	29	52	12	—	—	—	31	ocean
Cb	11	100	51	51	3	—	—	—	25	land
	11	100	37	55	2	—	—	—	33	ocean
Clear sky	22									land
	5									ocean
Sky obscured due to fog	1									land
	1									ocean

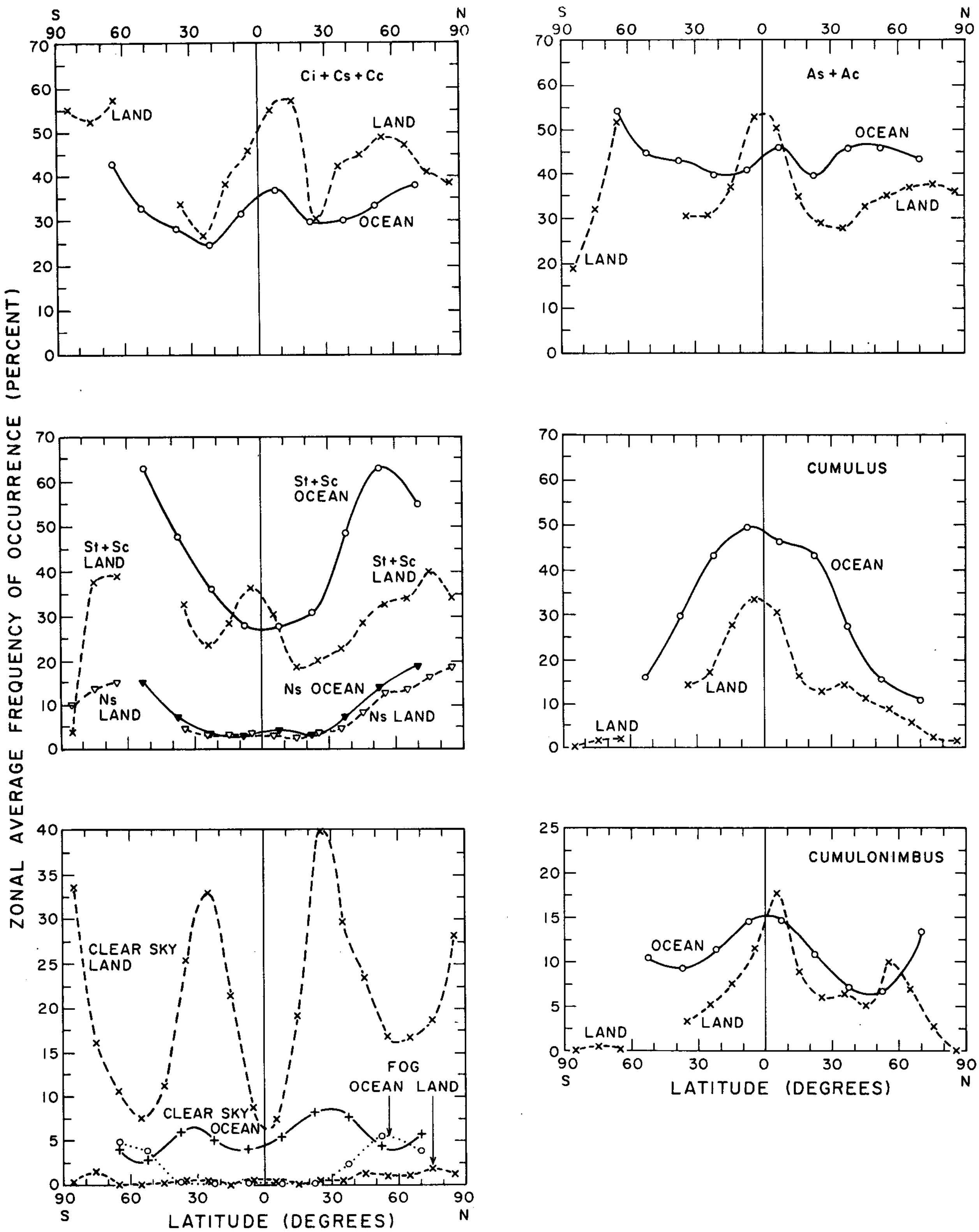

FIG. 1. Zonal, annual average frequency of occurrence of each cloud type, of clear sky, and of sky obscured due to fog, for land and ocean parts of each zone. ["Frequency of occurrence" is the fraction of weather observations in which a cloud type was reported present, given that it was possible to see whether it was present, irrespective of the fraction of the sky actually covered by that cloud.] A smooth curve is drawn through the points, which represent 10° zones over land and 15° zones over ocean (except for the high-latitude ocean zones 60°–80° N and 60°–70°S). The points are averages of all four seasons. Clear sky, fog, and cumulonimbus frequencies are plotted in the lower frames on an expanded scale. Gaps appear in most of the plotted values for land at 40°–60°S because the small amount of land there (less than 5%) often resulted in unrepresentative or meaningless zonal averages.

quantities, and which is discussed elsewhere (Hahn *et al.*, 1982, 1984).

If the contingency probability $P(A \Rightarrow B)$ is greater than $f(B)$, then one may say that A and B tend to be meteorologically associated [whereas if $P(A \Rightarrow B)$ equals $f(B)$, this means that B is just as likely to occur whether or not A is present]. The tables show for example that $P(As \Rightarrow Ci)$ generally exceeds $f(Ci)$. These two types actually exhibit the strongest association of any two of the six types, particularly over the ocean. By contrast, As and Cu tend to be somewhat mutually exclusive. This is likely due to the fact

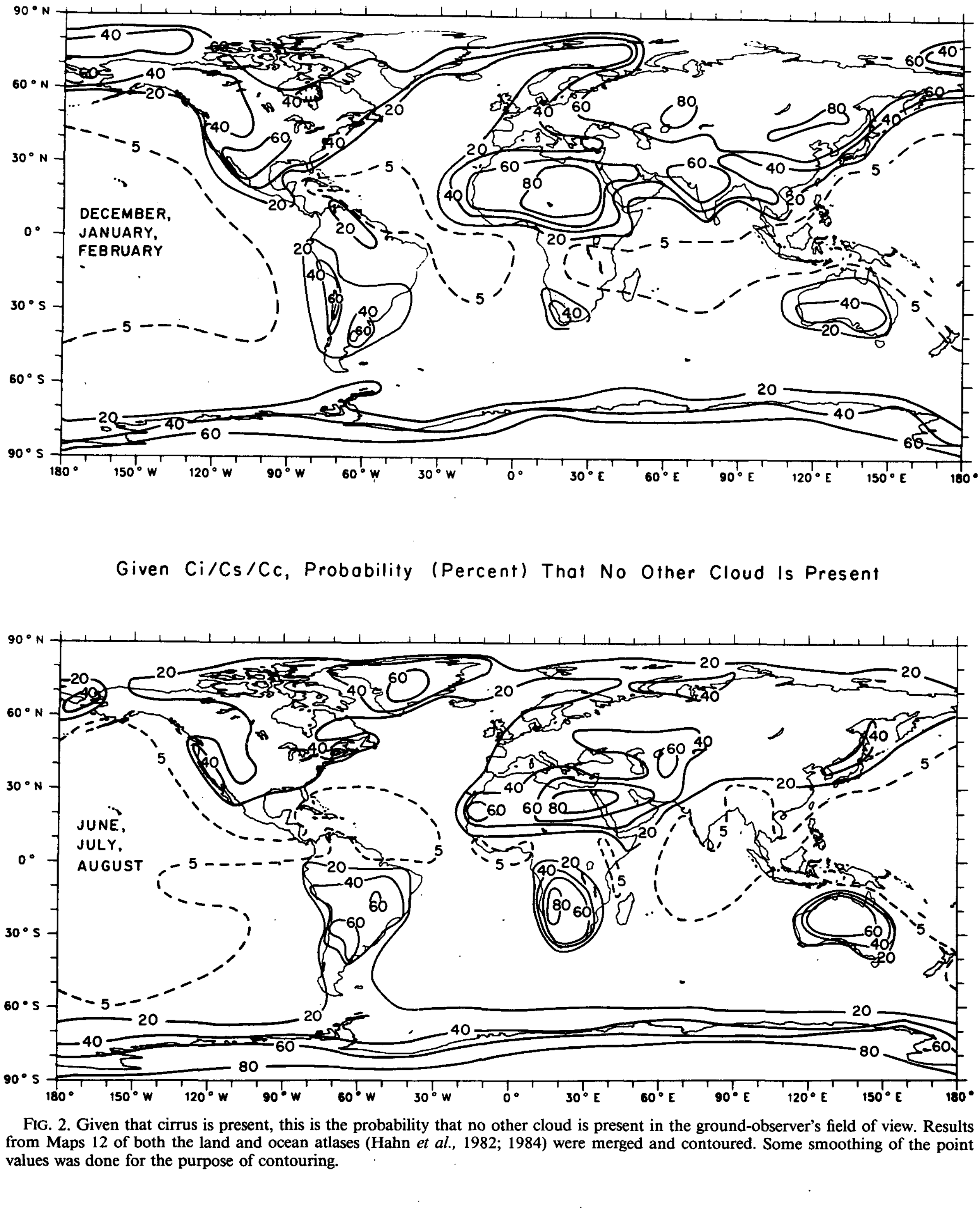

FIG. 2. Given that cirrus is present, this is the probability that no other cloud is present in the ground-observer's field of view. Results from Maps 12 of both the land and ocean atlases (Hahn *et al.*, 1982; 1984) were merged and contoured. Some smoothing of the point values was done for the purpose of contouring.

that Cu occurs in unstable air whereas As occurs in stable air. This tendency is strong over the ocean at low latitudes (30°N–30°S) and weak at higher latitudes. At high latitude, St and Ci show a tendency to be somewhat mutually exclusive, but no such tendency is seen at low latitude. $P(\text{Cb} \Rightarrow \text{Ci})$ exceeds $f(\text{Ci})$ in the tropics, where the Ci often originates from the top of a Cb cloud, but Ci and Cb show no strong association at higher latitude except in the summer.

The most dramatic difference between land and ocean is $P(\text{Ci} \Rightarrow \text{NO})$ and $P(\text{As} \Rightarrow \text{NO})$. The Ci and As types are much more likely to be found alone over land than over ocean.

Some of the co-occurrence probabilities are less meaningful than others, particularly with regards to nimbostratus which does not have a particular code number to itself in the synoptic code. We required that precipitation (rain or snow, but not thunderstorm) actually be occurring at the time of observation in order to define either a middle or low stratiform cloud as Ns. If the middle cloud type became classified as Ns then it had the possibility of co-occurring with low St; whereas only if Ns was classified from the low type (which happens rarely) could it co-occur with middle As. (Details are given in Table 1 and Figs. 1–3 of Hahn *et al.,* 1984.) The probabilities $P(\text{Ns} \Rightarrow \text{St})$, $P(\text{St} \Rightarrow \text{Ns})$, $P(\text{As} \Rightarrow \text{Ns})$, $P(\text{Ns} \Rightarrow \text{As})$, and $P(\text{Ns} \Rightarrow \text{NO})$ are therefore computed according to somewhat arbitrary definitions and are perhaps less useful than the other probabilities. A somewhat artificial distinction sometimes had to be made as to whether only a single nimbostratus cloud, or separate Ns and St clouds, were present. After completion of the ocean atlas, the class of reports which were considered to contain a reliable indication of "no other cloud" in the presence of Ns was revised. The values of $P(\text{Ns} \Rightarrow \text{NO})$ in Table 1 and 2 here, using the new computation, are considerably lower than those given in the ocean atlas. $P(\text{St} \Rightarrow \text{NO})$ was also slightly affected.

6. Geographical variations

Geographical variations, both of frequencies of occurrence and of co-occurrence probabilities, are much less smooth over land than over ocean. There are at least two reasons for this. One is that the surface conditions on land can exhibit great local variation, so that a station may not be representative of the total area of its box. Another is that any differences in observing procedure among individual observers, and among different countries, can affect the land areas much more than the ocean areas, because each grid box in the ocean is sampled by many different ships.

The geographical variations of these co-occurrence probabilities are discussed in the atlases referred to above. Only one example is given here in Fig. 2, showing $P(\text{Ci} \Rightarrow \text{NO})$ for two seasons. Cirrus is very rarely observed alone in the central ocean areas. The probability is larger near the coasts, and then increases rapidly as the coastline is passed. $P(\text{Ci} \Rightarrow \text{NO})$ averages 45% over land but only 9% over the ocean. The reason for this difference is, at least in part, because of the higher frequency of low clouds (Cu and St) over the oceans (Fig. 1). The highest values of $P(\text{Ci} \Rightarrow \text{NO})$ are in the descending branch of the winter hemisphere Hadley cell. In the midlatitudes of North America and Asia cirrus is also more likely to occur alone in winter, probably because the greater convective activity in summer generates low clouds. In addition, in middle and subpolar latitudes cirrus often represent the leading edge of the cloud systems associated with frontal activity which occurs more frequently during winter. This kind of information might be useful in planning field experiments such as the First ISCCP Regional Experiment (FIRE). Figure 2 shows that an experiment designed to study cirrus in isolation should probably be carried out over land rather than over the ocan, and in winter rather than summer.

Acknowledgments. The ship observations were made available to us by Ralph Slutz (CIRES). The observations from land stations were provided to the National Center for Atmospheric Research (NCAR) by J. Zuver of the Fleet Numerical Oceanography Center and made available to this project by Roy Jenne, Dennis Joseph and Gregg Walters of the Data Support Group of NCAR. The special data set of observations from weather ships and nearby transient ships was provided by R. Quayle (National Climatic Data Center). This work is supported as part of the International Satellite Cloud Climatology Project (ISCCP) by the National Climate Program Office of NOAA and by the Department of Energy, under Grant NOAA-NA80AA-D-00030.

REFERENCES

Bunker, A. F., 1976: Computations of surface energy flux and annual air-sea interaction cycles of the North Atlantic Ocean. *Mon. Wea. Rev.,* **104,** 1122–1140.

Caton, F. G., 1978: *Documentation and User's Guide for the FNWC Consolidated Data Set of Marine Surface Observations.* Rep. NOO228-78-D-4316, Meteorology International, Inc., Monterey, CA 93940, 14 pp.

Hahn, C. J., S. G. Warren, J. London, R. M. Chervin and R. Jenne, 1982: *Atlas of Simultaneous Occurrence of Different Cloud Types over the Ocean.* NCAR Tech. Note TN-201 + STR, 212 pp. [NTIS PB83-152074.]

——, ——, ——, ——, and ——, 1984: *Atlas of Simultaneous Occurrence of Different Cloud Types Over Land.* NCAR Tech. Note TN-241 + STR, 214 pp.

Quayle, R. G., 1980: Climatic comparison of estimated and measured winds from ships. *J. Appl. Meteor.,* **19,** 142–156.

Riehl, H., 1947: Diurnal variation of cloudiness over the subtropical Atlantic Ocean. *Bull. Amer. Meteor. Soc.,* **28,** 37–40.

——, 1978: *Introduction to the Atmosphere.* 3rd ed. McGraw-Hill, 410 pp.

Woodbury, G. E., and M. P. McCormick, 1983: Global distribution of cirrus clouds determined from SAGE data. *Geophys. Res. Lett.,* **10,** 1180–1183.

World Meteorological Organization, 1974: *Manual on Codes, Vol. 1,* WMO Publ. No. 306, Geneva.