DEPARTMENT OF INDUSTRY AND COMMERCE
METEOROLOGICAL SERVICE

TECHNICAL NOTE No. 21

AIRCRAFT ICING OVER THE EASTERN NORTH ATLANTIC

BY

P. K. ROHAN, M.A.
AND
F. Ó hAONGHUSA.

DECIMAL INDEX
551.574.7(261)

DUBLIN
OCTOBER 1956

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INTRODUCTION:

A considerable proportion of aeronautical engineering literature is devoted to the results of recent research in de-icing and anti-icing methods. In spite of the advances made possible by this research, ice accretion on the external surfaces of aircraft continues to be a serious hazard to safe and regular flight operations. Experienced pilots regard ice accretion as one of the most dangerous meteorological conditions which can arise and airline operators in some countries at least, have regulations which prohibit the release of flights into zones of severe icing and restrict the release of flights into zones of lesser icing intensity.

The meteorologist providing service to aeronautical interests is continually faced with the problem of forecasting the location and intensity of icing conditions. Renewed interest in research in cloud physics in recent years, stimulated by the theories of rain formation put forward by Bergeron (1935) and by Findeisen (1938), has contributed much to the forecaster's knowledge of factors governing the formation of ice on aircraft, but the forecasting of icing conditions continues to be a problem with special difficulties. These difficulties arise from a lack of standard measurements of the relevant meteorological parameters, the great variability of these parameters within relatively small areas and over short durations, and the difficulty of obtaining standard measurements and achieving uniform classification of icing intensity.

The meteorological variables of importance in determining the rate of ice accretion are as follows:-

a) Ambient temperature.

b) The effect of air speed on the temperature of the surface exposed to icing.

c) Liquid water content per unit volume of cloud.

d) Diameter of water droplets.

The meteorologist can determine the first two of these with reasonable accuracy with the aid of synoptic charts, the reports of upper air temperature ascents, and a knowledge of the air speed involved.

Measurements of (c) and (d) are not normally available and the forecaster has to depend on knowledge of the origin and stage of development of the cloud formation to estimate whether there is a sufficient density of supercooled water droplets of dimensions suitable for ice accretion in clouds. In doing this, it is necessary to take geographical influences into account since particular cloud formation in one region may have a significantly different structure, in so far as aircraft icing is concerned, from the same type of cloud in another region. Thus, experienced airmen tell us that the icing conditions in the top of cumulonimbus in tropical thunderstorms are far more severe than anything met in middle latitudes.

This paper gives an analysis of the aircraft reports received at Shannon directly from aircraft in flight in the Shannon/Prestwick Flight Information Region (F.I.R.) in the 12-month period October, 1953 to September, 1954, inclusive, in an effort to provide some information on the meteorological conditions favourable for ice formation in that particular area and on the frequency with which various intensities of icing are reported. The boundary of the Shannon/Prestwick F.I.R. is shown in Figure 1.

Non-meteorological factors which influence the ice accretion on the forward surfaces of an aircraft are associated with the design of the aircraft. Thus, while meteorologists can determine the effect of air-speed on the temperature of the surface exposed to icing, the effect of variations due to airspeed is frequently masked, as different ranges of airspeed are frequently associated with differences in aircraft type each with particular aerodynamic characteristics influencing the aircraft's vulnerability to ice accretion. This paper gives some tabular data on the frequency with which different aircraft types reported ice over the year under review.

Classification of Aircraft Icing:

Because a satisfactory icing rate meter for routine use on commercial aircraft is not yet available, reports on the occurrence of icing on the outer surface of commercial aircraft are based on non-instrumental observations. This method of reporting intensity is necessarily subjective and is influenced by aircraft parameters which are difficult to compare. However, Perkins (1952) reports that actual comparisons made in the United States between the total ice accretion values given by measurements on an icing rate meter and the pilot's estimate of the icing intensity, based on his observations of accumulation of ice on the frame of one type of aircraft and the corresponding effects on aircraft performance, are very consistent.

The severity of icing is related to the rate of ice accretion on the frame of an aircraft and in civil flights may be reported as "light", "moderate" or "heavy."

Light icing is reported when the accumulation of ice presents no serious hazard and can be dispersed by operating de-icing equipment.

Moderate icing is reported when the de-icing equipment provides marginal protection, the ice continues to accumulate but not at a rate sufficiently fast to affect the safety of the flight unless it continues over an extended period of time.

Heavy or severe icing is reported when ice builds up rapidly in spite of de-icing procedures. Heavy icing may cause marked alteration in speed or altitude and, if continued over a period, would seriously affect the safety of the flight.

Reports of icing using this classification, while related to the rate of ice accretion, are also influenced by the characteristics of the particular aircraft and the type of de-icing equipment used.

Aircraft Weather Reporting Procedure:

During the period to which this survey refers, every transport aircraft flying over the North Atlantic Ocean and operating in accordance with ICAO procedures was required to make and record a meteorological observation at hourly intervals at the same time as the position report was made. These observations were sent with the position report via the air-ground communications channels to the appropriate Air Traffic Control centre and were passed immediately to the associated Meteorological Office. In the Shannon/Prestwick FIR, the hourly aircraft weather reports were in this way received at Shannon either directly from the aircraft or in collective bulletins from Prestwick. The vast majority of the reports from the Shannon/Prestwick FIR were received at Shannon either by direct transmission to Shannon or were intercepted by Shannon in transmission to other Communications centres. All reports received from the FIR were disseminated in collective bulletins to other Meteorological offices.

The reports were received in code (POMAR) or in an abbreviated plain language form. They normally included, in addition to the position, altitude and time of the observation, observations of flight conditions, wind, corrected temperature, pressure data, cloud and weather as observed at flight level and some operational information of a non-meteorological character (e.g. fuel aboard). Details of turbulence and icing encountered were added as appropriate, but "nil" reports were not made when no icing or turbulence was reported. In the period under review some, but not all, aircraft reported airspeed and some reports included remarks on weather phenomena observed (e.g., frontal passages) which are always very useful to the forecaster.

Prior to September, 1954, icing reports in coded (POMAR) messages were classified as light, moderate or heavy with an indication of the time within the last hour at which the icing was observed together with particulars of whether the icing occurred in cloud or precipitation. The form introduced in September, 1954, which was the last month of the survey, restricted the classification of icing to light, moderate, and severe without reference to the exact time of occurrence or the medium in which icing was experienced. Considering weather reports from aircraft as aids in the provision of meteorological service to flights, this change was a retrograde step as reports on the new form left the meteorologist in considerable doubt as to the extent of the area in which icing occurred, though of course with a number of reports in a particular area it was frequently possible to determine from aircraft reports the limits of the area in which icing occurred. This is however no longer possible in 1956 since with the introduction of a procedure in which reports are made at specified meridian lines, the spatial distribution of weather reports no longer exists and it is no longer possible to indicate from even a large number of aircraft reports the extent of an area in which hazardous conditions such as icing exist.

Distribution of Aircraft Reports in the Shannon/Prestwick FIR:

In the 12-month period under review, reports were not at hand for 4 full days (27th, 28th October, 7th November and 17th January) but in the remaining 361 days 37,746 aircraft reports were received at Shannon direct from aircraft in flight over the Shannon/Prestwick Oceanic FIR. The distribution of these reports over the area is shown in Figure 1. The figures on the diagram represent the total number of reports for each 1-degree space over the entire 12 months. To facilitate extraction and tabulation of data, reports from the shaded portion on the edge of the F.I.R. South-west of Shannon as shown in Figure 1 were excluded from the survey.

No weather report was received from any aircraft above 25,000 feet which may be regarded as the operating ceiling of the types of commercial aircraft operating over the North Atlantic at that time. Reports were received from aircraft at heights spaced at 1,000 feet intervals from 25,000 feet downwards. Westbound and Southbound aircraft operated at even heights (2,000, 4,000, 6,000 feet, etc.), while Northbound and Eastbound operated at odd heights (3,000, 5,000 feet, etc.)

The reports have a marked concentration in the area between latitudes 50°N and 55°N where over 70% of the total number occur. The density of reports falls off to the North of 55°N and is considerably less South of 50°N. In three 1-degree spaces no aircraft weather observation was made in the entire 12 months.

The largest number of reports was received from the degree-space bordered by 53°N, 54°N, 13°W and 14°W. This maximum total of 1,066 reports representing an average of a little less than 3 reports per day for all heights is probably due to the fact that aircraft departing Shannon Westbound were very frequently in this space at the end of the first hour of flight.

The frequency of aircraft weather reports on the North Atlantic has a marked diurnal variation with a maximum number of reports per hour being received in the hours between 0200 and 0600 GMT. and a minimum in the early afternoon (1200/1800 GMT.). There is also a marked variation over the year in the number of reports received per day, due to the seasonal pattern of trans-Atlantic flight frequency with heavy schedules in the Summer months and light schedules in the Winter months.

Analysis of Aircraft Reports of Icing:

In the Shannon/Prestwick FIR, 582 reports of icing were received from aircraft in flight in the FIR in the 12-month period. This total includes a few cases where freezing rain or freezing drizzle was reported without specific mention of icing, it being assumed that such phenomena would invariably result in ice accretion. It was further assumed that, in such circumstances, in the absence of specific reference, icing would be moderate.

The number of icing reports received, representing 1.5% of the total number of aircraft reports in the FIR suggests that the incidence of icing conditions is smaller over the Eastern North Atlantic than over Canadian air routes where it is estimated that aircraft spend about 5% of their flying time in icing conditions (value quoted by Schaetzel, 1955). While one would expect differences in the frequency of icing over the two areas with such marked climatic differences particularly as regards temperature, the figures cannot be directly related due to differences in the pattern of flight operations. Over the Atlantic most flights operate at heights above 10,000 feet and can frequently avoid flying through cumuliform cloud. Transocean flights can be and frequently are planned to avoid areas of suspected icing conditions. A large proportion of domestic flights over America operate below 10,000 feet where it is not so easy to avoid cloud. With the airways system it is not quite so easy to plan to avoid areas of suspected icing conditions. Differences in the type of aircraft used in the two areas would also make it difficult to compare the occurrence of icing conditions in the two areas.

Figure 2 shows the geographical distribution of icing reports over the Shannon/Prestwick FIR in the period under review. The variation of icing with longitude is such as could be due to random sampling. The variation of icing with latitude is shown in Table 1. While there may be a significant variation with latitude in the distribution of aircraft reports at different heights influencing the latitudinal distribution of icing reports in the FIR., Table 1 suggests a small but definite tendency for icing to occur at higher latitudes.

Table 1 - Variation of Icing with Latitude in the Shannon/ Prestwick Oceanic FIR, October, 1953 to September, 1954

Latitude	No. of Reports		Percentage frequency
	With Icing	Total	
61N			
	24	1346	1.78
59N			
	51	1942	2.63
57N			
	93	4120	2.26
55N			
	198	12007	1.65
53N			
	160	11563	1.38
51N			
	44	4394	1.00
49N			
	5	1244	0.40
47N			
	4	608	0.66
45N			
	3	522	0.57
43N			
Total	582	37746	1.54

Table 2 gives a summary of the reported occurrence of different intensities of icing each month.

Table 2. - Summary of occurrence of icing of different intensities each month.

Month	No. of Aircraft Reports	No. of reports of Icing				Percentage frequency
		Heavy	Moderate	Light	Total	
Oct., 1953	2,820	1	15	35	51	1.8
Nov., 1953	2,367	3	15	35	53	2.2
Dec., 1953	2,684	3	14	28	45	1.7
Jan., 1954	2,477	1	11	33	45	1.8
Feb., 1954	2,078	3	12	28	43	2.1
Mar., 1954	2,441	3	13	25	41	1.7
Apr., 1954	2,909	1	3	31	35	1.2
May, 1954	3,588	0	7	33	40	1.1
June, 1954	4,161	0	3	27	30	0.7
July, 1954	4,037	1	4	26	31	0.8
Aug., 1954	4,042	1	7	47	55	1.4
Sept., 1954	4,142	3	18	92	113	2.7
Total:	37,746	20	122	440	582	1.5

Frequency of icing conditions appears to be higher in Winter months than in Summer.

The high frequency in September, 1954 is believed to have been abnormal for that time of year.

No icing was reported in 135 of the 361 days. No icing was reported on 9 consecutive days on two occasions in the period (10th-18th April, inclusive, and 21st-29th June, inclusive), while on one day (23rd September, 1954) 11 reports of icing were received. 9 of these cases were observed between 0000 and 0700 GMT. and at heights which varied from 12,000 to 21,000 feet.

Figures 3 and 4 give the surface and upper air flow over the area at that time.

A summary of the number of occasions on which different numbers of icing reports were received per day over the period is given in Table 3.

Table 3. - Number of days on which various numbers of cases of Icing were reported - period October, 1953/ September, 1954

No. of reports of Icing per day	0	1	2	3	4	5	6	7	8	9	10	11
No. of days on which the given number occurred	135	80	51	39	29	11	9	3	2	0	1	1

With an average of 1.6 reports of icing per day the above figures indicate coherence as we would expect in the occurrence of reports of icing conditions. Taking into account the fact that on the basis of meteorological advice and being aware of other aircraft reports, aircraft can plan or deviate from plan to avoid serious icing conditions it is very probable that Table 3 understates the coherence in the incidence of icing in the North Atlantic.

On the other hand, on very many occasions an aircraft reported ice in a particular position while numerous other aircraft passing through that position within a short time of the reported icing did not experience icing conditions. The very variable nature of the occurrence of icing conditions has been well illustrated by Mason (1953) who reported during de-icing tests off Iceland that on one occasion in a lenticular cloud a heavy rate of icing was observed for about 2 minutes before the aircraft flew into less dense stratus cloud. In order to get back into the icing conditions a precise procedure turn was made and although the aircraft passed through the cloud within yards of the previous track, no ice formation occurred and the cloud was by then composed of ice crystals.

It was noted that two cases of heavy icing were never observed in one day or in consecutive days.

Aircraft Icing and Ambient Temperature:

The temperature observations included in the aircraft weather reports were investigated in order to get an indication of the relation between the occurrence of ice accretion and the ambient temperature over the area.

The corrected temperature readings from a thermometer suitably installed on a commercial transport aircraft can give a good approximation of the true ambient temperature (ICAO Circular II). While a number of temperature reports do not reach a high standard of accuracy, it was felt that in general the aircraft corrected temperature reports give a good indication of the ambient temperature.

Of the 582 reports of icing, 9 were associated with reported positive temperatures. Minus 42°C was the lowest temperature reported with an icing report. This case occurred in January, 1954. 95% of the icing reports were associated with temperatures between 0° and -25°C. Figure 5 gives the distribution of ice reports with different temperatures in that range, in the Winter (October/March) and Summer (April/September) half years.

It can be seen from these figures that the modal temperature for ice accretion is approximately -7°C in Winter and -5°C in Summer. This figure is somewhat lower than reported for icing surveys in cloud over the United Kingdom by Bigg (1937) who found maximum frequency in the range of temperatures between -3°C and -5°C and less than suggested by Benum and Cameron (1944) over the Canadian Rockies in Winter where the modal temperature was -13°C. Pettit (1953) found, however, in more recent Canadian investigations that the modal point was about -6°C. The distribution of ice reports in relation to temperature appears to be more even over the Eastern North Atlantic than the figures for the U.K. or Canadian Rockies would suggest. Pettit (loc. cit.) reporting on Canadian investigations stated that 90% of all encounters occurred at temperatures above -13°C. The corresponding figure for temperatures above -13°C in the present investigation is 63%.

Airspeed and Altitude Effects:

The effects of differences in airspeed and altitude on the accretion of icing over the North Atlantic is difficult to evaluate from the data examined. The majority of aircraft reporting operated within a fairly narrow common range of airspeeds while the aircraft which operated below that range were mainly of one type (DC4) with its own limited range of operating airspeed and altitude, and with its own aerodynamic characteristics.

The distribution of reports for different altitudes for each type of aircraft operating over the North Atlantic is not uniform, as each aircraft type has optimum operating altitudes in particular circumstances.

Table 4 gives the distribution of reports from the more common type of aircraft at the various altitudes in the period under review and the distribution of icing reports from each type of aircraft.

Table 4. - Distribution of reports with height from six types of aircraft operating over the Shannon/Prestwick Oceanic FIR, October, 1953/September, 1954. (Distribution of icing reports for the same aircraft shown in brackets)

Height	TYPE OF AIRCRAFT						TOTAL
	St'cr.	Sup, Con	Con	DC-6	DC-4	CANADAIR	
7000 or below	60 (1)	9	96 (1)	109 (1)	817(12)	5	1096 (15)
8000	148 (1)	27	202 (1)	1036(27)	1714(50)	41 (1)	3168 (80)
9000	23 (1)	12	116 (4)	187 (5)	1983(33)	11 (1)	2332 (44)
10000	911(21)	210(4)	615(17)	1377(31)	181 (4)	75	3369 (77)
11000	24 (1)	17	101 (3)	171 (5)	127 (6)	11	451 (15)
12000	583 (9)	528(7)	307 (6)	1425(35)	4	14	2861 (57)
13000	106	79(2)	190 (1)	561 (7)	10	19	965 (10)
14000	613(16)	605(4)	269(11)	1863(37)	4	82 (1)	3436 (59)
15000	320 (4)	81(1)	416(10)	1433(27)	0	47 (1)	2297 (43)
16000	183 (2)	119	542 (4)	764(12)	0	27	1635 (18)
17000	257 (1)	153(1)	2453(18)	1200(22)	0	317 (3)	4380 (45)
18000	184	294	3235(25)	364 (7)	0	26	4103 (32)
19000	850 (5)	583	1499 (5)	1423(26)	0	32	4387 (36)
20000	33	278(1)	97	58 (1)	0	1	467 (2)
21000	435 (9)	646(2)	244 (2)	546 (4)	0	1	1872 (17)
22000	1	20	0	1	0	0	22
23000	157 (2)	115	15 (1)	30	0	0	317 (3)
24000	0	1	0	0	0	0	1
25000	61 (1)	8	0	1	0	0	70 (1)
Total:	4949(64)	3785 (22)	10397 (109)	12549 (247)	4840 (105)	709 (7)	

Examination of the data from which Table 4 was compiled indicated that there was a significant variation in the distribution of reports, in the different ranges of altitude throughout the year. In view of this, it was not feasible to test the significance of the observed variation of icing with altitude.

Association between Icing and Turbulence:

It was noted that a considerable number of reports of icing were associated with reports of turbulence.

In the data examined, 366 cases of turbulence were encountered and 121 of these cases were reported simultaneously with icing.

Table 5 shows the frequency of icing reports in relation to turbulence.

Table 5 - Frequency of Simultaneous Occurrence of Icing and Turbulence

	No Icing	Icing	Total
No turbulence	36919	461	37380
Turbulence	245	121	366
Total:	37164	582	37746

Even though the first column includes reports at temperatures which would not admit of icing, the Tables indicate that icing and turbulence are associated. The percentage frequency of 1.0% for turbulence and 1.5% for icing as indicated by the above table should not, however, be taken to represent the probability of encountering turbulence or icing at levels now being flown on the North Atlantic. As known or forecast areas (or levels) of turbulence or icing will, in general, be avoided, these figures may be regarded as representing minimum probabilities for the phenomena.

Summary of Synoptic Situations in which Icing was reported:

Measurements of the liquid water content per unit volume of cloud or of the diameter of the water droplets in the atmosphere are not made by commercial aircraft and are not available for use by the forecaster. He must rely on his knowledge of the state of development of cloud formations and synoptic characteristics as well as reports from aircraft in the area in which he is interested to decide on the probability of ice formation.

An examination of the synoptic situations in which icing occurred in this survey gives the following results:-

Table 6 - Summary of Occurrence of Icing in different Situations

Synoptic Characteristics	Intensity of Ice			Total
	Light	Moderate	Heavy	
Warm Front	140	37	6	183
Cold Front	107	26	2	135
Occlusion	44	14	2	60
Warm Air Mass	33	10	3	46
Cold Air Mass	116	35	7	158

The incidence of icing in occlusions was confined almost exclusively to the Summer months, no icing reports associated with occlusions being reported in the months December to April, inclusive, and only one report of icing in an occlusion was reported in the month of November. Cold Front icing was more common in the Winter months. The incidence of icing in Warm Fronts or Air Masses did not show any marked seasonal variations. Cloud formations at high levels in cold air masses can be avoided more frequently in flight over the North Atlantic and only 30% of the cases of icing in such air masses occurred at heights above 12,000 feet. The risk of ice in cumulo type cloud is probably considerably greater than the figures in Table 6 would suggest.

Acknowledgments:

We are indebted to various members of the staff of the Meteorological Office at Shannon Airport for assistance in the tabulation of the data and for suggestions at all stages of the work.

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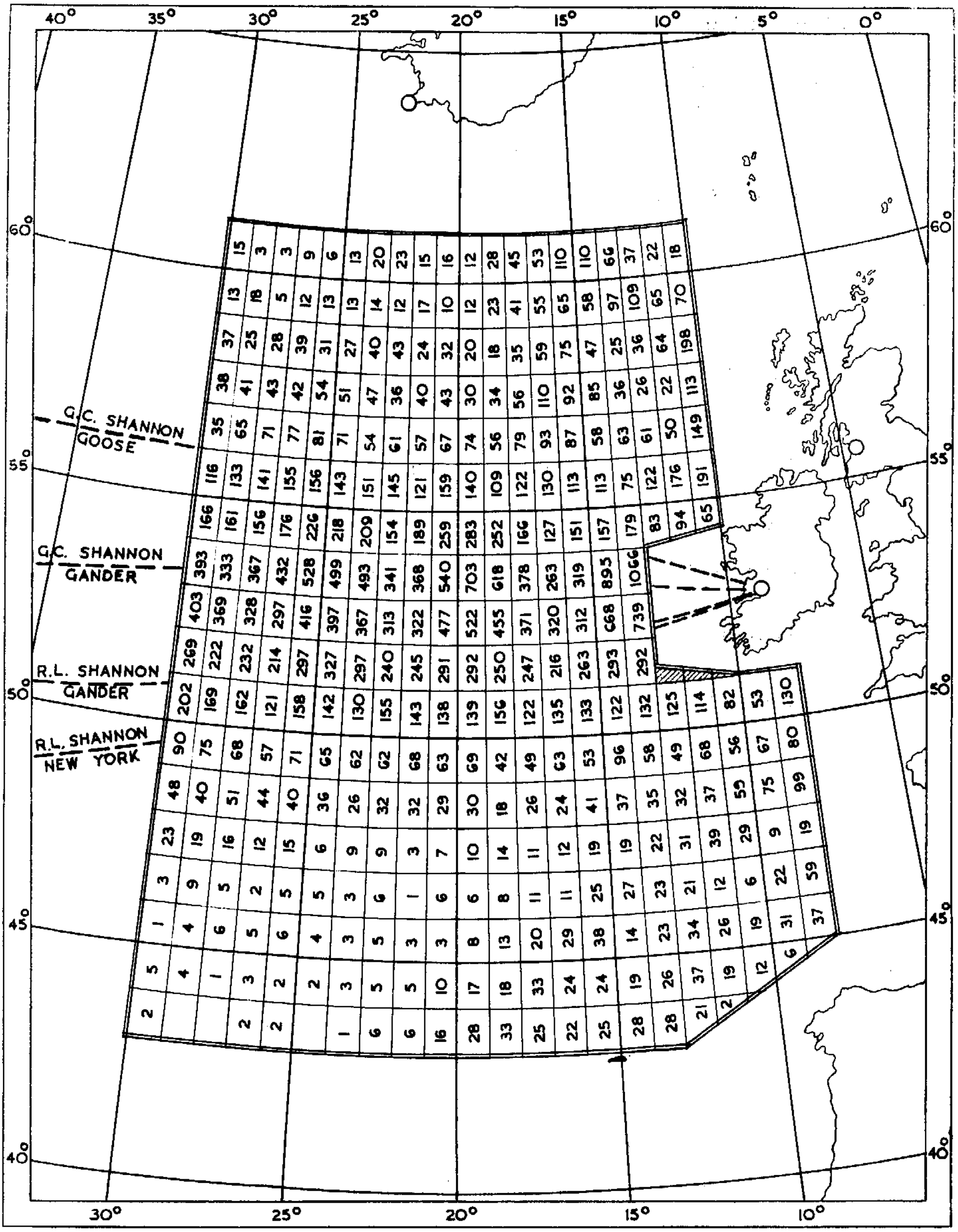

Fig. 1. Distribution of Aircraft Weather Reports in the Shannon/Prestwick Flight Information Region (FIR) for the year October, 1953-September, 1954

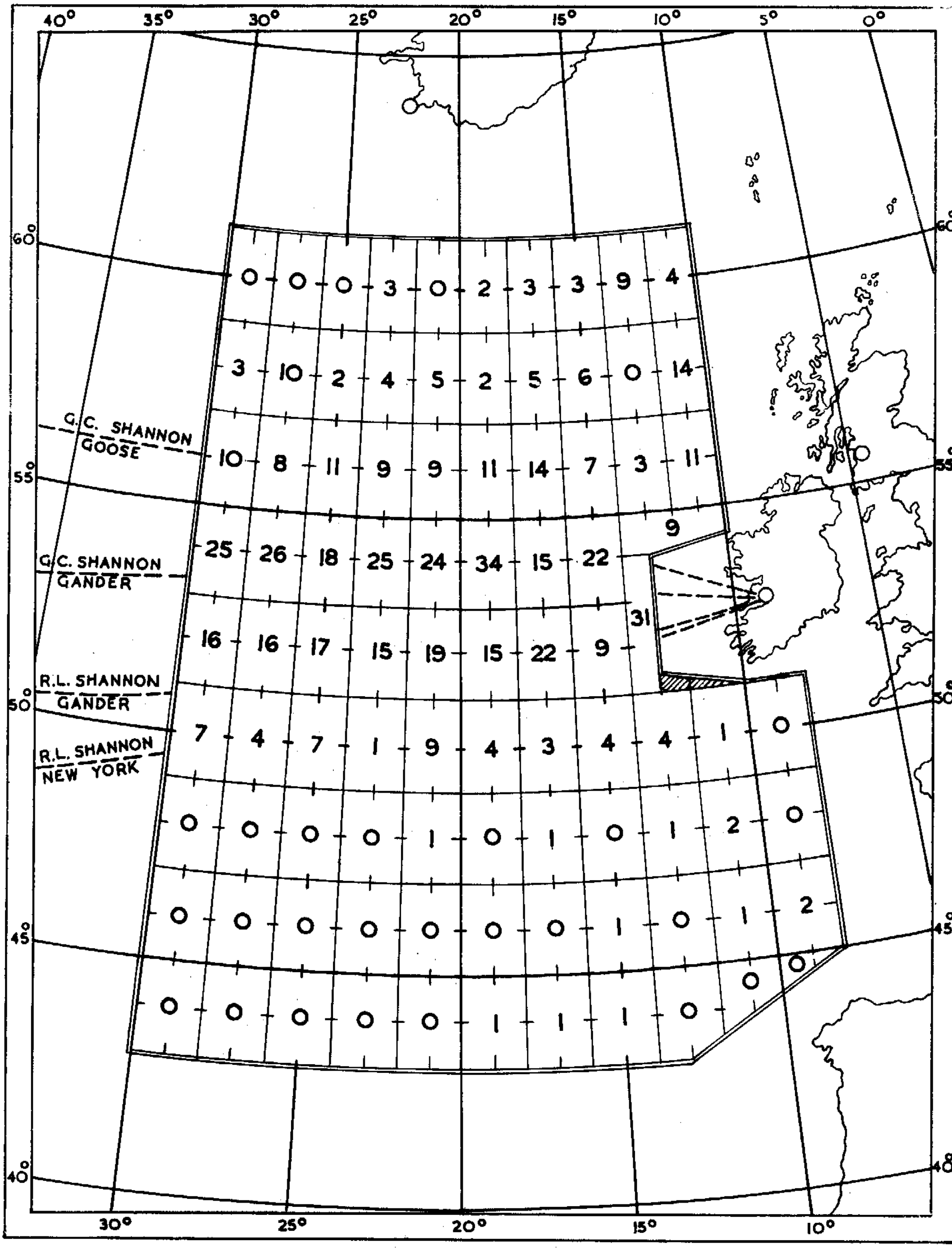

Fig. 2. Distribution of reports of ice accretion on aircraft in the Shannon/Prestwick Flight Information Region (FIR) for the year October, 1953–September, 1954.

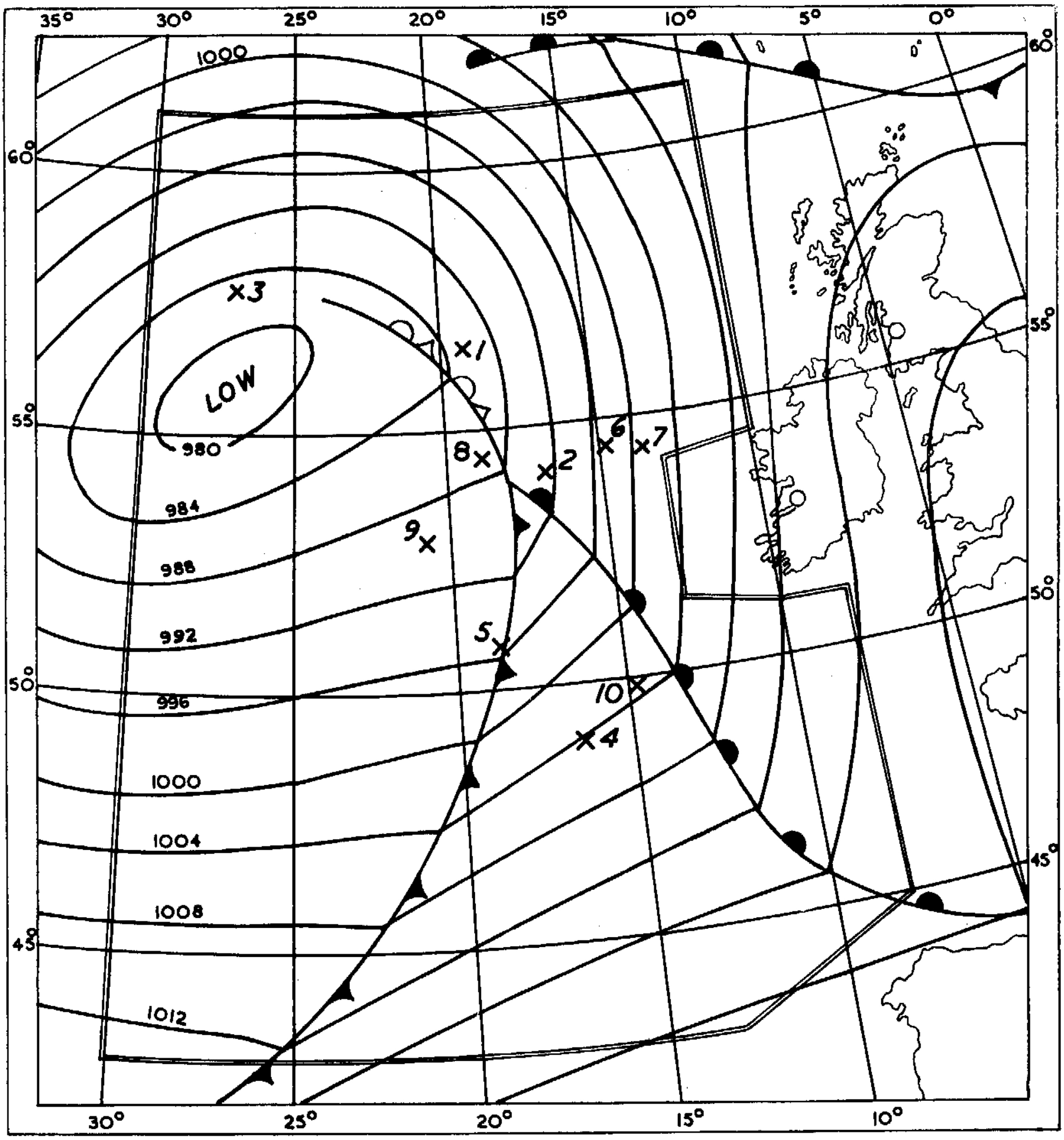

Fig. 3. Surface chart 0600 GMT. 23rd September, 1954, showing positions of reported ice accretion.

1. 2335 GMT. 22nd Sept. Light Ice at 12000 ft.
2. 0015 GMT. 23rd Sept. Severe Ice at 15000 ft.
3. 0035 " " " Light Ice at 12000 ft.
4. 0113 " " " Light Ice at 21000 ft.
5. 0148 " " " Light to Moderate Ice at 21000 ft.
6. 0316 " " " Light Ice at 17000 ft.
7. 0346 " " " Light Ice at 16000 ft.
8. 0449 " " " Light Ice at 18000 ft.
9. 0522 " " " Light to Moderate Ice at 17000 ft.
10. 0644 " " " Moderate Ice at 15000 ft.

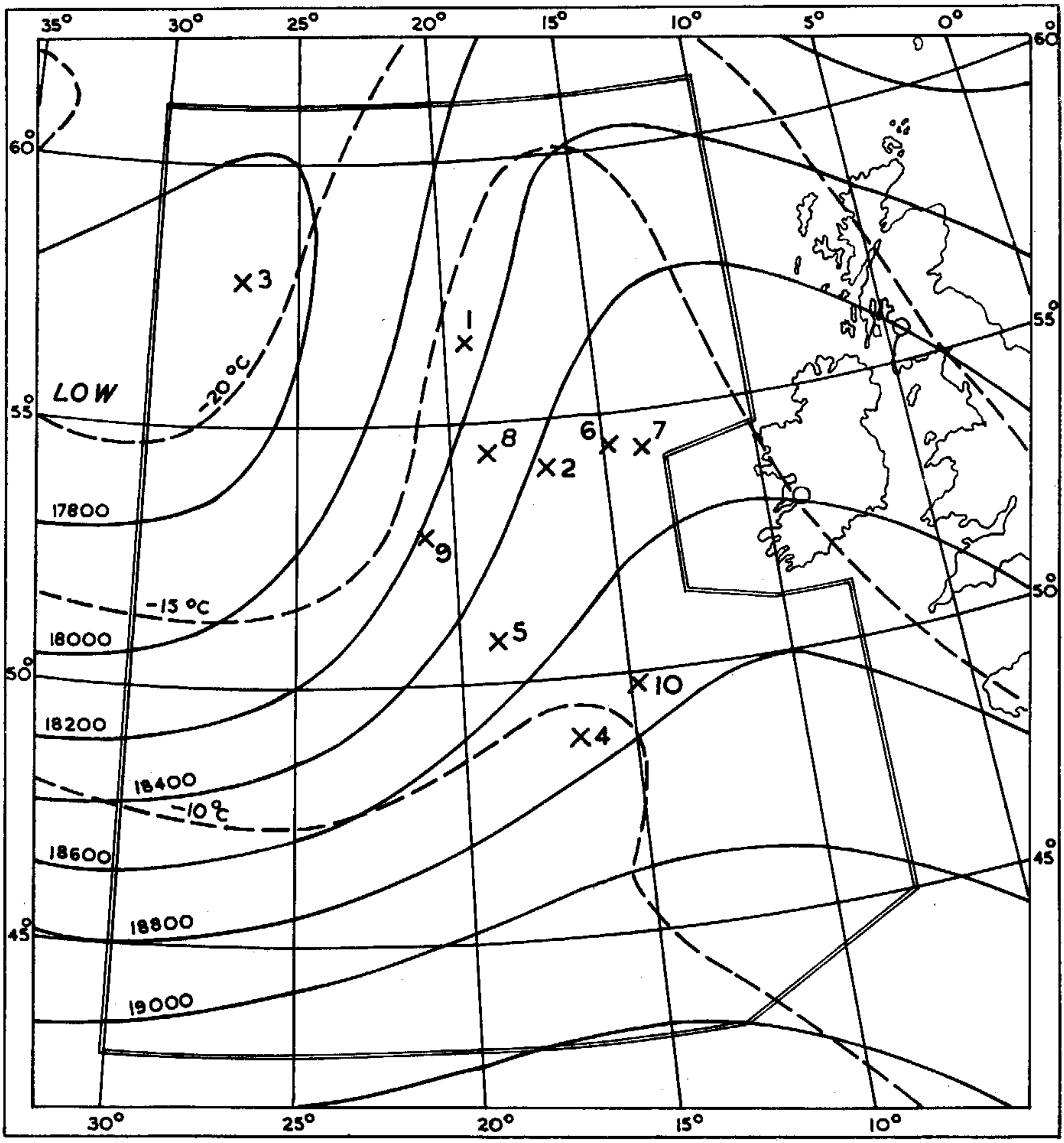

Fig. 4. 500 mb. chart 0300 GMT. 23rd September, 1954

1. 2335 GMT. 22nd Sept. Light Ice at 12000 ft.
2. 0015 GMT. 23rd Sept. Severe Ice at 15000 ft.
3. 0035 " " " Light Ice at 12000 ft.
4. 0113 " " " Light Ice at 21000 ft.
5. 0148 " " " Light to Moderate Ice at 21000 ft.
6. 0316 " " " Light Ice at 17000 ft.
7. 0346 " " " Light Ice at 16000 ft.
8. 0449 " " " Light Ice at 18000 ft.
9. 0522 " " " Light to Moderate Ice at 17000 ft.
10. 0644 " " " Moderate Ice at 15000 ft.

HISTOGRAMS OF ICE ACCRETION IN THE SHANNON/PRESTWICK OCEANIC F.I.R. WITHIN THE TEMPERATURE RANGE +1 TO −25°C

FREQUENCIES EXPRESSED AS PERCENTAGES. THE INTERVAL OF TEMPERATURE IS 3° CELSIUS.

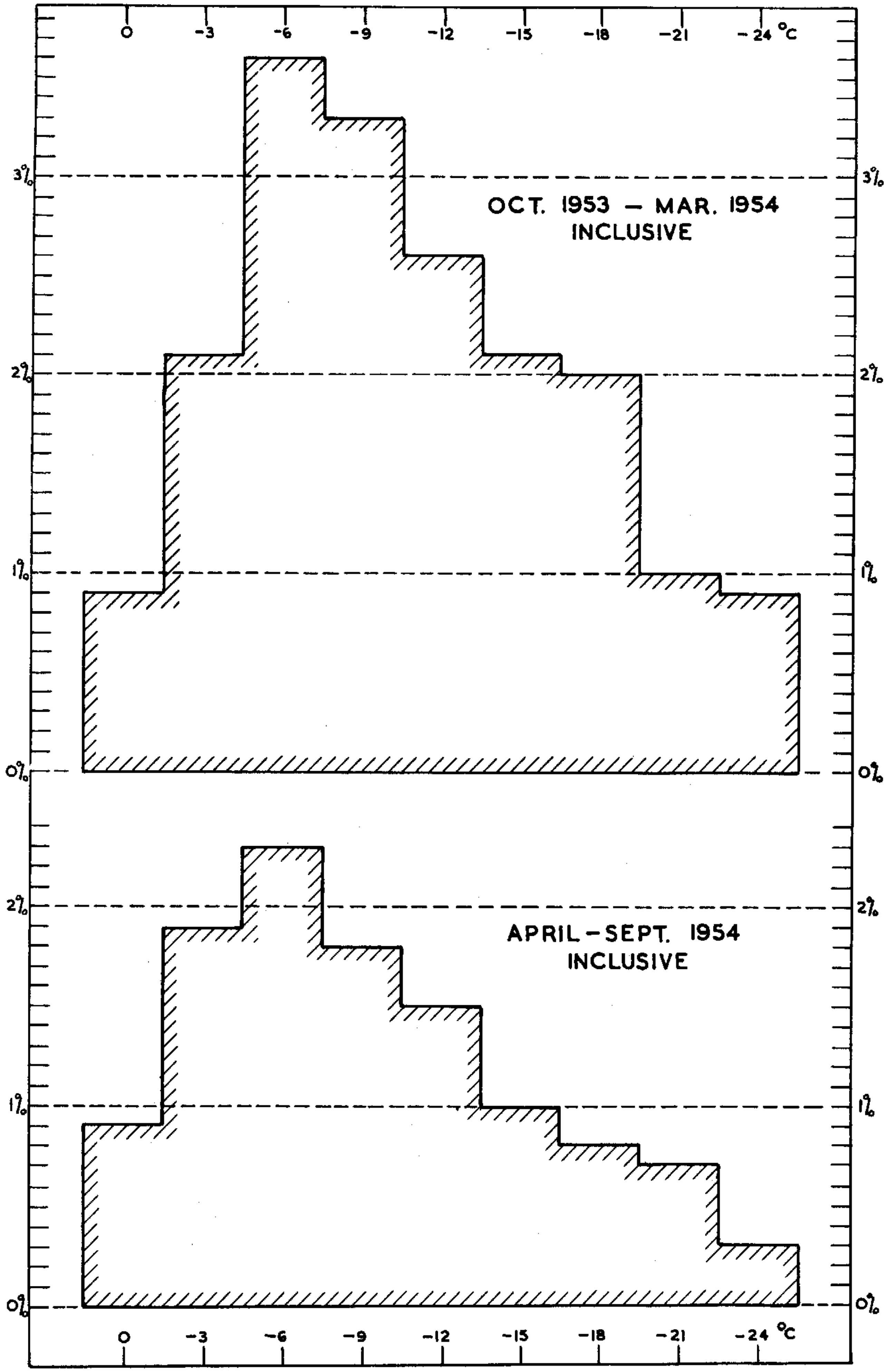

Fig. 5