Interim Report R&D Project 207

Influences of Cloud Cover on Utility of NOAA/AVHRR imagery for Snow Cover Monitoring over England and Wales

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INFLUENCES OF CLOUD COVER ON UTILITY OF NOAA/AVHRR IMAGERY FOR SNOW COVER MONITORING OVER ENGLAND AND WALES

by

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INFLUENCES OF CLOUD COVER ON UTILITY OF NOAA/AVHRR IMAGERY FOR SNOW COVER MONITORING OVER ENGLAND AND WALES

1. GENERAL INTRODUCTION

The purpose of this study is to establish the extent to which cloud obscures the land surface so limiting the value of NOAA-AVHRR imagery as a tool for the assessment of snow cover. The operational value of snow cover assessment by such imagery will depend on the relationship between cloud occurrence and availability of satellite imagery during periods when snow is present. Cloud free images are likely to be most valuable during the periods of snow ablation, as a guide to the rate of melting, and during periods immediately prior to ablation when estimates of the potential water equivalent of the snow present can be made.

It must be stressed that the methods being developed under this contract do not depend on wholly cloud-free imagery. The GIS inputs to the method are intended to allow extrapolation under cloud cover when only part of the satellite imagery of the snow areas is cloud free. In addition, a sequence of satellite images, where different parts of each image are cloud free, can be overlaid to produce fuller areal information. Present work on both the GIS inputs and on the superimposing methods is encouraging and can reduce reliance on cloud free, or largely cloud free images.

The first section of the study (Section 2) uses hard-copy images to establish the general extent and distributions of cloud, in the presence of snow, for England and Wales as a whole and for three Water Authority areas.

The second section of the study (Section 3) contains a further analysis of the possible cloud cover constraint on the operational use of the imagery. The data inputs are in part as for Section 2 but include further data from the Meteorological Office archive for selected ground stations.

2. ANALYSIS OF NOAA-AVHRR HARDCOPY IMAGES

2.1 Introduction

NOAA-AVHRR are sensors carried by a family of sun-synchronous, polar orbiting satellites, which are c.850 km above the Earth and through their High Resolution Picture Transmission (HRPT) mode provide six to eight images daily of the United Kingdom at a 1.1 km ground resolution in the visible and thermal infrared wavelengths of the electromagnetic spectrum. The emissivity and reflectivity of the ground and the lower troposphere are detected in these wavelengths. Snow and cloud are highly reflective in the visible wavelengths, although in the infrared, snow is dull (see Table 1). Based on these physical characteristics, a low-cost technique to distinguish snow from cloud over ground surfaces can be developed. Experience gained from earlier visual and objective analyses of NOAA imagery over the UK has suggested that useful assessments of ground conditions (including snow cover) can be made by subjective inspection of archived hard-copy image data providing that cloud cover is not in excess of 75 per cent (Djavadi and Cracknell 1986). To be effective, such a visual inspection method should be based on as large a data set as possible (see Barrett and Curtis 1982). For present purposes the NOAA-AVHRR archived images are ideal, as they provide twelve years of consistent data, amounting to 538 days (each containing 3-6 images) for the winters of 1979-1991. For more detailed and objective results, recourse to substantial sets of digital data would be necessary. The budget for the present study precluded a digital approach. However, given the resource the possibility of a fuller digital assessment of cloud cover and operational use of AVHRR data exists.

Table 1 Appearances of snow and cloud on visible and infrared images.

WAVELENGTH	SNOW	CLOUD
VISIBLE	Very bright	Bright
INFRARED	Dull	Bright

2.2 Background and method

The method used to assess the degree of cloud cover over England and Wales and, in particular, the following three Water Authorities (as designated and proposed for the present study by the National Rivers Authority (NRA)): Welsh, Severn-Trent, and Northumbrian, was by visual inspection of the hardcopies of the NOAA-AVHRR imagery. This involved eyeball inspection of the infrared and visible waveband images for the twelve year period of 1979-1991. Using a magnifying glass on a tripod, daily evaluations of cloud cover in winter snow days were made for the day-time images where available in accordance with the categories used by Djavadi and Cracknell (1986): these were 0-25, 26-50, 51-75, and 76-100 per cent cloud cover. Snow evaluations for each day-time image were also undertaken and ascribed to a "snow" or "no snow visible" category. Percentages were then calculated to allow comparisons to be made between the cloud categories and amongst the twelve years examined.

There are several factors contributing to the choice of this method. These included the following:

(a) Cost and Availability. Twelve years of NOAA-AVHRR imagery are archived at the University of Dundee Satellite Receiving Station and can be accessed free of charge, or copies may be made cheaply upon request. The images give information for a wide areal coverage which is unobtainable from available ground point measurement networks, and they are especially useful for examination of inaccessible highland areas above recording stations where accumulations are likely to be at their maxima.

(b) Ease of Interpretation. The Dundee archive hardcopies of visible and infrared images (23 x 15 cm in size, with the UK approximately 5 x 2 cm in size, before magnification) can be interpreted easily for general cloud cover contents (see examples 1-3 in the Appendix III). In this regard a synergistic approach was adopted, using ground data to validate the satellite picture interpretations. This involved the use of three ground data sources. These were: the annual "*Snow Survey of the British Isles*" reports (presenting daily data); the "*Daily Weather Reports*" (published by the Meteorological Office) and the periodical publication "*Hydrological Data for the UK*" (published by the British Geological Survey). These data sources provided information of daily snow conditions on the ground at 0900 GMT, the atmospheric conditions where the snow survey data have not yet been published (e.g. for the winter of 1990-1991), and the precise delineation of the Water Authority regions, respectively.

(c) Image resolution. The Thematic Mapper sensor on Landsat or the Multispectral mode on SPOT provide extremely expensive imagery very infrequently - about one pass every sixteen days - and output images of inappropriate ground resolution (20 - 30 m) for studies of large areas of the British Isles. On the other hand, the SSM/I passive microwave data are of insufficient ground resolution (at best 15 x 13 km) for present purposes, are available only since 1987, and are not readily available to the wider scientific community at this stage. As indicated in the Introduction, the NOAA-AVHRR imagery falls between those two extremes, both in terms of cost and resolution.

(d) Previous experience. NOAA-AVHRR images form the basis for the Bristol Ice and Snow Cover Algorithm (BRISCA) used successfully in both previous and present snow area delineation studies (see Bailey et al. 1991).

One entirely different possibility was considered, namely to assess the frequency of cloud cover and snow on the ground over the UK from conventional (ground-based) observations. This would have involved the use of Meteorological Office records which give detailed accounts of low, medium and high cloud, and snow lie, for about eighty stations over the UK. However, the cloud records alone were quoted at a purchase price of £120 per month per station. Therefore this option was rejected on the grounds of the prohibitive cost given the large amount of data required for a study at the intended scale.

Limited use was made of the Meteorological Office records of cloud cover in Section 3 of this study for selected stations. The data were not purchased but were inspected at the Meteorological Office Archives. This personal inspection facility was free of charge.

2.3 <u>Results and discussion</u>

Cloud cover percentages were estimated for each snow day between 1 October and 31 March for winters of 1979-1991. Table 2 exemplifies the results for a period which

Table 2 Snow days with different levels of cloud cover (expressed as %) as estimated from NOAA-AVHR visible and infrared imagery for February and March 1986.

Date	Welsh Water Authority						Severn-Trent Water Authority					
	Level of cloud cover (%)				snow visible		level of cloud cover (%)				snow visible	
	0-25	26-50	51-75	76-100	yes	no	0-25	26-50	51-75	76-100	yes	no
20.2.86			*			*	*					*
21.2.86	*					*	*					*
22.2.86			*		*			*			*	
23.2.86		*			*			*			*	
24.2.86		*			*			*			*	
25.2.86				*	*				*			*
26.2.86	*				*					*	*	
27.2.86		*			*					*	*	
28.2.86	*				*					*	*	
29.2.86	*				*					*	*	
1.3.86	*				*					*	*	
2.3.86	*				*					*	*	
3.3.86			*			*		*				*
4.3.86				*		*				*		*
TOTAL	6	3	3	2	10	4	2	4	1	7	9	5

Table 2 (cont.) Snow days with different levels of cloud cover (expressed as %) as estimated from NOAA-AVHR visible and infrared imagery for February and March 1986.

Date	Northumbrian Water Authority						England and Wales					
	Level of cloud cover (%)				snow visible		level of cloud cover				snow visible	
	0-25	26-50	51-75	76-100	Yes	No	0-25	26-50	51-75	76-100	Yes	No
20.2.86				*		*			*			*
21.2.86				*		*		*				*
22.2.86	*				*		*				*	
23.2.86	*				*		*				*	
24.2.86	*				*		*				*	
25.2.86				*	*					*	*	
26.2.86	*				*					*	*	
27.2.86				*	*					*	*	
28.2.86	*				*					*	*	
29.2.86	*				*					*	*	
1.3.86	*				*					*	*	
2.3.86	*				*					*	*	
3.3.86		*				*			*		*	
4.3.86				*		*				*	*	
TOTAL	8	1	0	5	10	4	3	1	2	8	12	2

included a significant snow event in February/March 1986. Table 3 presents results for each winter season through the 12-year study period in percentages of snow days falling in each cloud cover category, plus percentages of days with snow ("YES") or no-snow ("NO") visible on the images.

It emerged that half of the photos examined contained less than seventy-five per cent cloud coverage in the selected NRA regions. As noted earlier, these are considered useful for operational snow monitoring by previous techniques. Past studies have shown that above this threshold (i.e. of greater than 75 % cloud cover) ground visibility is insufficient for monitoring changes in ground features (see Djavadi and Cracknell 1986). However, a proportion of these images may still be useful for the assessment of snow cover over the UK, especially if there is a long period of snow cover (e.g. of four to eight days) if extrapolation from cloud free days is possible (see Lucas 1989). Moreover, the cut-off point of 75 % cloud cover does not take spatial distribution in to account: full appreciation of each scene is needed, in conjunction with ground data, in order to precisely locate the cloud and to relate it to the snow-line. Thus, more than half of the photos examined have potential use for operational snow monitoring by previous techniques, though with the implementation of GIS extrapolation and image overlay techniques the 75% cut off may be over pessimistic in some cases. In about one-third of all cases cloud cover is relatively limited (below 50%).

At the bottom of Table 3 is the yearly average percentage of snow days with different levels of cloud cover expressed as percentage. It is shown that cloud coverage was similar in all three NRA regions and consistent with the overall picture for England and Wales, with Northumbria being the most cloudy and Severn-Trent the least cloudy. Djavadi and Cracknell (1986), in their study for the whole of Britain, produced results broadly corroborating this study: they found 50 % of the scenes were less than 75 % cloud covered.

To assess the confidence in the visual analysis of AVHRR hardcopy images, the visual inspection results were compared with the results of computer classified NOAA AVHRR images, for selected days as reported by Lucas (1989). The days chosen were 24, 25 and 29 January 1986 and 22-28 February 1986. The results revealed a close agreement between the two studies using different types of AVHRR data. There was, however, a tendency for the visual inspection method to slightly over-estimate cloud cover. Low solar illumination in winter months resulting in darker visible hardcopy images may, at least in part, account for this over-estimation. Earlier studies using visual inspection methods also confirm their tendency to over-estimate cloud cover (see Barrett and Curtis 1982).

Table 3 Annual percentage of snow days with different levels of cloud cover (cloud cover expressed as percentage).

Date	Welsh Water Authority						Severn-Trent Water Authority					
	Level of cloud cover (%)				% snow visible		Level of cloud cover (%)				% snow visible	
	0-25	26-50	51-75	76-100	Yes	No	0-25	26-50	51-75	76-100	Yes	No
1979-80	12	7	12	70	29	71	17	12	7	65	25	75
1980-81	17	7	12	64	35	65	19	3	14	65	22	78
1981-82	36	15	11	38	70	30	38	9	21	32	72	28
1982-83	9	7	18	66	27	73	9	16	7	68	21	79
1983-84	21	8	15	56	38	62	23	13	15	48	30	70
1984-85	30	14	14	42	50	50	32	10	20	38	48	52
1985-86	21	11	19	49	27	73	21	14	21	45	23	77
1986-87	0	14	14	72	11	89	0	25	14	61	4	96
1987-88	13	33	7	47	20	80	27	27	0	47	20	80
1988-89	16	24	8	52	40	60	12	12	36	40	8	92
1989-90	10	5	24	62	14	86	14	10	24	52	14	86
1990-91	26	22	15	37	52	48	22	11	22	45	52	48
YEARLY AVERAGE	18	14	14	54	32	68	20	13	17	50	28	72

Table 3 (cont.) Annual percentage of snow days with different levels of cloud cover (cloud cover expressed as percentage).

Date	Northumbrian Water Authority						England and Wales					
	Level of cloud cover (%)				% Snow visible		Level of cloud cover (%)				% Snow visible	
	0-25	26-50	51-75	76-100	Yes	No	0-25	26-50	51-75	76-100	Yes	No
1979-80	14	12	3	71	24	76	15	15	5	65	36	64
1980-81	21	5	9	65	28	72	17	5	21	57	40	60
1981-82	45	17	17	21	77	23	32	15	30	23	79	21
1982-83	18	9	16	57	36	64	11	7	21	61	41	59
1983-84	34	7	10	49	43	57	21	18	26	35	54	46
1984-85	22	12	14	52	40	60	26	18	24	32	56	44
1985-86	24	9	16	51	36	64	18	21	28	33	42	58
1986-87	4	7	11	79	7	93	7	11	32	50	14	86
1987-88	33	0	20	47	20	80	33	13	13	41	33	67
1988-89	4	20	16	60	4	96	12	28	28	32	16	84
1989-90	33	0	24	43	24	76	19	14	24	43	24	76
1990-91	15	7	19	59	44	56	22	11	22	45	59	41
YEARLY AVERAGE	22	9	15	54	32	68	19	15	23	43	41	59

Note. Samples have been taken based on the reported snow days. The percentages of YES/NO snow indicate whether snow is visible or not on the hardcopy images.

3. FURTHER ANALYSIS OF ATMOSPHERIC CONSTRAINTS

The general picture that arose from Section 2 suggested the need for cloud cover evaluations in more detail, e.g. through an examination of selected individual stations using ground-based Meteorological Office records.

3.1 Cloud amount and frequency for periods of snow accumulation, stability and ablation

The data for the levels of cloud cover as a percentage from the hard-copy examination cited in Section 2 were assigned to periods of snow accumulation, stability and ablation. The assignation related in the first instance to England and Wales. These data are presented in Table 4. The three periods were identified in the case of each image by the use of the Daily Weather Report. The three periods were identified using the following criteria:

Accumulation: Consecutive days showing increasing snow depth.

Stability: Consecutive days with identical depths i.e. no reported snowfall or depth change.

Ablation: Consecutive days showing a decrease in the snow depth, or a specific station report indicating general melting.

A study of Table 4 shows that only in those cases with 76-100% cloud cover is there a marked difference between the yearly average percentages of snow days in the three categories. In the periods of snow accumulation and ablation, higher percentage of snow days fell into the group of 76-100% of cloud cover.

Even so, more than half of the images appear to have potential use for operational snow monitoring which agrees with the overall picture/conclusion drawn in Section 2. The study did not reveal greatest limitations of cloud during melt periods, when satellite snow data may be most useful to NRA. The cloud cover for snow accumulation period took the lead in this case.

3.2 Probability of getting snow data prior to melt

Similarly, statistics of the minimum cloud amount when snow depths are at or near maximum for an event have been derived and used as a means of determining the probability of getting/not getting any snow data prior to melt. Again, based on the data for the whole England and Wales, the result shows that more than half of the images (51%) considered have less than 75 % cloud cover (see Table 5), representing, it could be argued, real operational possibilities.

3.3 Cloud occurrence for snow days with above and below zero air temperatures

Ground data of concurrent cloud, snow cover and temperature from the UK Meteorological Office archives was used to establish the relationships between cloud and periods of snow stability and accumulation, and cloud and periods of snow melt.

The diagnostic characteristic of a period of snow accumulation or stability was that the temperature at 0900Z was equal to or below zero with presence of snow at the ground.

The diagnostic for a period of snow melt was that the temperature at 0900Z was above zero

Table 4 Yearly average percentage of snow days with different levels of cloud cover under different phases for England and Wales.

Level of cloud cover (%)	0-25	26-50	51-75	76-100
Accumulation period:	16.6	12.7	24.4	46.3
Stability period:	31.8	19.1	21.4	27.7
Ablation period:	16.3	15.7	23.6	44.4

Table 5 Percentage of snow days with different levels of cloud cover for England and Wales when snow depths are at or near maximum.

Level of cloud cover (%)	0-25	26-50	51-75	76-100
% of snow days	17.6	5.9	27.5	49.0

with snow at the ground. The choice of 0900Z for the air temperature value was determined by the archive material, it being the only value available to cover the required period at the selected stations. The diurnal variations of air temperature clearly represent a complication and it may be that days diagnosed as stability period or accumulation period days could be, for part of the 24 hour period, a period of melt.

The three stations selected for analysis were Great Dun Fell, Widdy Bank Fell and Low Etherley. They are chosen mainly because of their different altitudes; all three are in the NRA Northumbrian region. A summary of the results for each station is presented as follows.

1). Station: GT Dun Fell NGR: 3710/5322 Altitude: 847 m

Analysis was based on the 0900Z daily climate returns for the period 1979-1984.

Percentage of occasions with snow and temperature below zero in each okta class of cloud and fog. No. = 288.

Oktas	0	1	2	3	4	5	6	7	8	Fog
%	9.0	3.1	4.2	2.4	2.4	2.8	2.1	6.3	7.6	60.1

74% (7 – Fog)

76.1% (6 – Fog)

Percentage of occasions with snow and temperature above zero in each okta class. No. = 93.

Oktas	0	1	2	3	4	5	6	7	8	Fog
%	4.3	0	0	2.2	1.1	3.2	0	4.3	3.2	81.7

89.2% (7 to Fog)

2). Station: Widdy Bank Fell NGR: 3818/5298 Altitude: 513 m

Data used are the 0900Z daily climate returns for the period 1979-1987.

Percentage of occasions with snow and temperature below zero in each okta class of cloud and fog. No. = 426.

Oktas	0	1	2	3	4	5	6	7	8	Fog
%	0.7	9.4	4.5	3.5	4.7	4.9	7.3	19.0	29.1	16.9

65% (7 to Fog)

72.3% (6 to Fog)

Percentage of occasions with snow and temperature above zero in each okta class. No. = 234.

Oktas	0	1	2	3	4	5	6	7	8	Fog
%	0	0.4	0	2.6	4.7	6.8	8.1	26.5	29.5	21.4

77.4% (7 to Fog)

85.5% (6 to Fog)

3). Station: Low Etherley NGR: 4169/5289 Altitude: 155 m

Data used are the 0900Z daily climate returns for the period 1979-1987.

Percentage of occasions with snow and temperature below zero in each okta class of cloud and fog. No. = 147.

Oktas	0	1	2	3	4	5	6	7	8	Fog
%	1.4	10.2	10.9	6.1	6.1	4.8	18.4	14.3	23.1	4.8

42.2% (7 to Fog)

60.6% (6 to Fog)

Percentage of occasions with snow and temperature above zero in each okta class. No. = 123.

Oktas	0	1	2	3	4	5	6	7	8	Fog
%	0.8	6.5	12.2	3.3	8.9	5.7	16.3	14.6	28.5	3.3

45.4% (7–Fog)

62.7% (6–Fog)

Thus, the potentially greater limitations of cloud have been revealed in melt periods in the analysis of such data for the selected stations. Whether this will affect the operational use AVHRR images for the NRA needs careful consideration before any conclusion is drawn.

3.4 Breakdown of frequency and amount of clouds between upland and lowland

One may notice in the previous Section that the three stations chosen were also at very different altitudes. The results corroborated the possibility of coincidence of snow cover and cloud cover in mountain areas which might restrict the usefulness of the images even in periods with regional cloud cover significantly less than 75%. However, it may also be suggested that snow in mountain areas may not make the greatest and most direct contribution to flood by snow melt.

4. CONCLUSIONS

The visual inspection method employed in this study provided a cheap, quick and reasonably reliable means of assessing possible cloud cover constraints on the use of NOAA-AVHRR snow algorithms over the UK. This method can be usefully augmented by the examination of selected ground data measurements, which are detailed local samples of the snow coverage in areas of interest and these together can help to asssess the operational potential of remote sensing methods of snow cover assessement.

The visual inspection technique has provided a useful, consistent and accessible set of data which indicate a significant number of occasions on which remote sensing methods can be applied.

Addressing one of the seven objectives in Stage II of this Contract (see Bailey et al. 1991), this study has shown that on average at least 50% of the winter images considered have direct potential utility for operational uses of the NOAA-AVHRR snow algorithm, and that regional variations in cloud cover are generally slight, dense cloud cover being most frequent (54%) in Northumberland and least frequent in Severn-Trent (48%). However, if the cloud imagery is used in conjunction with a GIS data base the percentage of usable images can be significantly increased. Furthermore, often more than one AVHRR image is available for snow study on a given day, and this also increases the possibilities of improved mapping of snow by satellite because clouds move. Classified snow areas from two or more images can be overlaid through GIS to get fuller extent of snow distribution for the same snow day or for a snow event. Finally, recourse to passive microwave imagery will further improve operation possibilities (Bailey *et al.* 1991). SSM/I data are presently expected to provide snow area, snow depth and snow water equivalent information for all but about 10% of all cases, although even this figure may be improved upon as research to distinguish precipitation from snow already on the ground proceeds.

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APPENDICES

I Water Authority Boundaries

II An Example of the Overlay Used to Define the Three Water Authority Regions in England and Wales During Visual Analysis

KEY

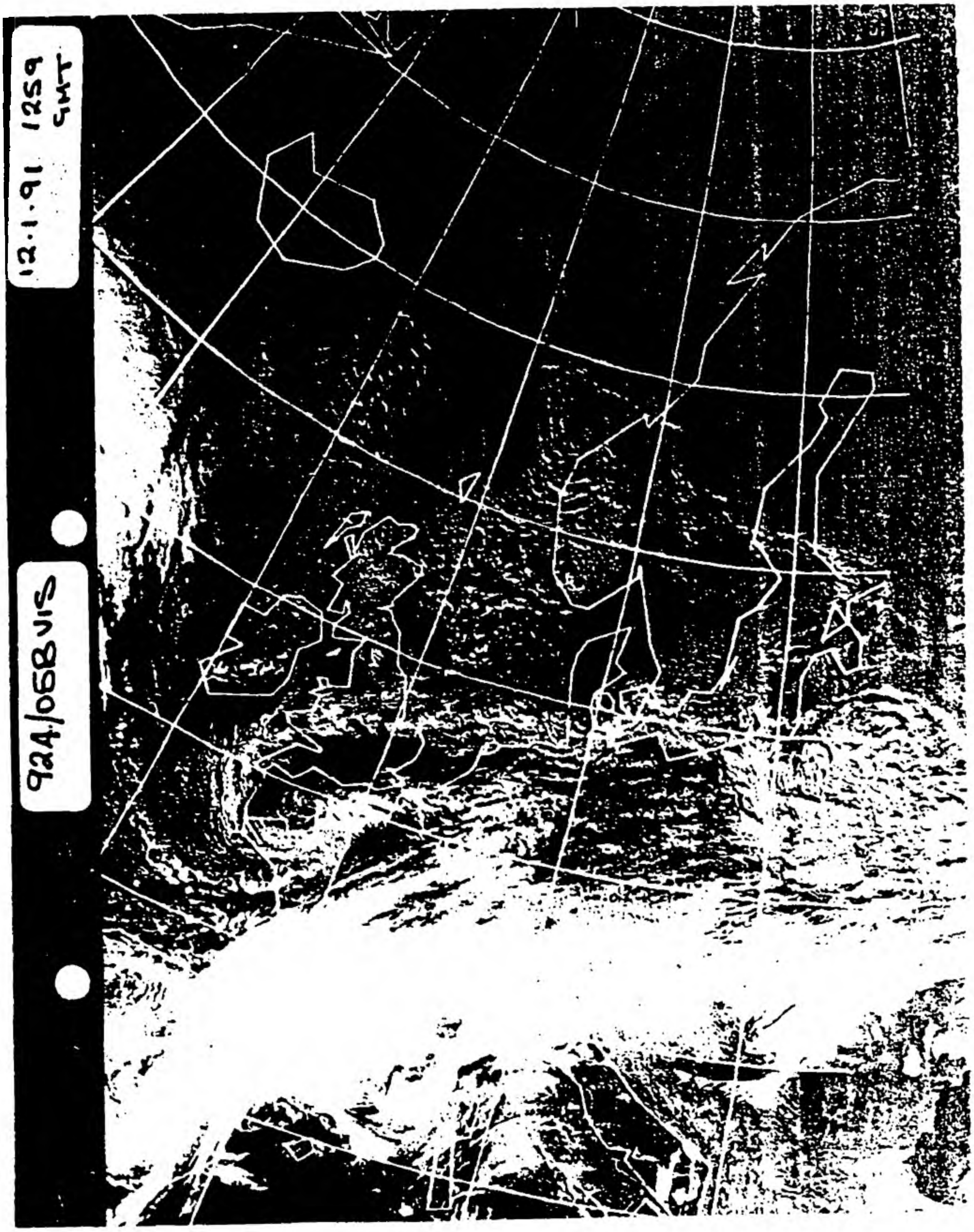
1: Wales

2: Severn-Trent Water Authority

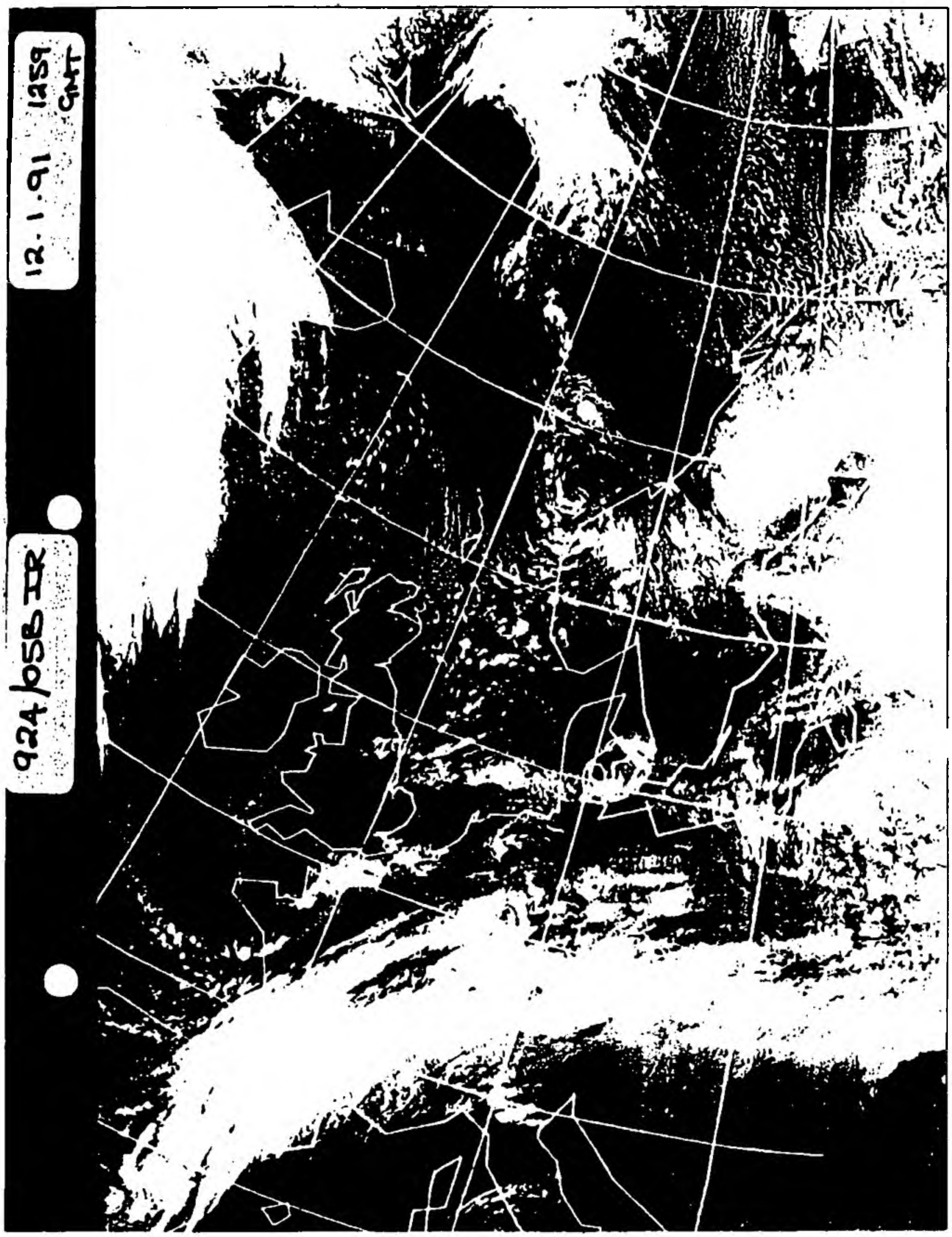
3: Northumbria Water Authority

Source: Hydrometric Data and Statistics (1988); reduced to 7% of the original size.

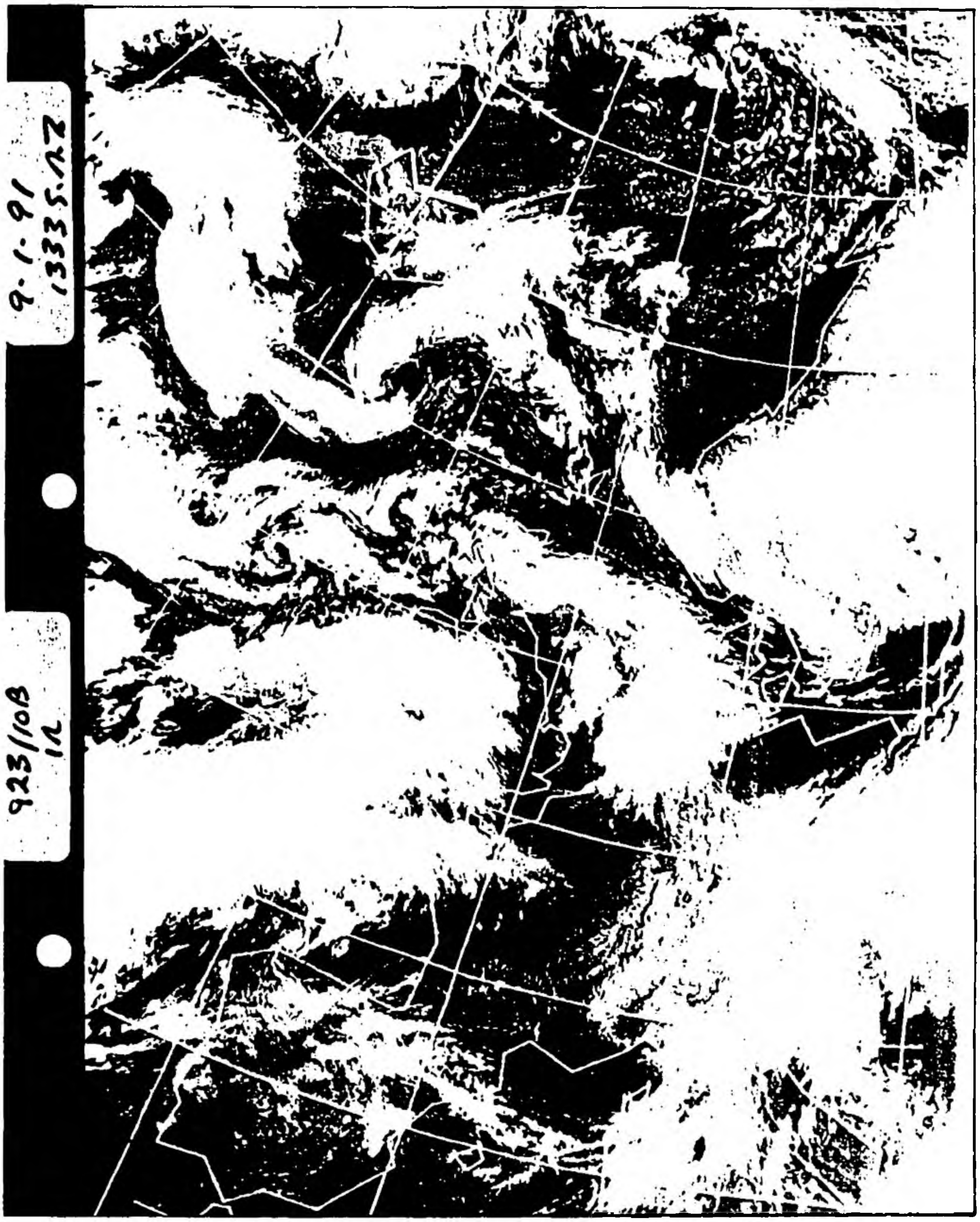
III Xerox of the Visible Hardcopy Images



Example 1: Xerox of the Visible Hardcopy Image for 12.1.91. A useful scene for operational snow monitoring over the UK.



Example 2: Xerox of the Infrared Hardcopy Image for 12.1.91: A useful scene for operational snow monitoring: cloud cover less than 25 % over the UK.



Example 3: Xerox of the Infrared Hardcopy Image for 9.1.91: this scene is generally too cloudy for operational snow monitoring although some areas of the UK are cloud free (e.g. Northumbria).