Nordic Hydrology, 25, 1994, 39-52

The Potential of Satellite Remote Sensing of Snow over Great Britain in Relation to Cloud Cover

Paper Presented at EGS XVII General Assembly
(Edinburgh, GB – April 1992)

D.R. Archer
National Rivers Authority, Newcastle upon Tyne, GB

J.O. Bailey, E.C. Barrett and D. Greenhill
Dept. of Geography, University of Bristol, GB

Whilst satellite monitoring of snow cover is already operational in some countries, the maritime climate of the United Kingdom poses special problems for assessment of snow cover by satellite, including the short snow duration, its intermittent occurrence and associated conditions of cloud. Both satellite and ground-based observations of cloud have been used to assess the limitations imposed by cloud over broad regions and also for individual sites at different elevations and during periods of snow accumulation, stability and ablation. It is concluded that satellite sensing based on visible and infrared images alone is restricted by cloud cover, but can often provide helpful ancillary information in support of ground based measurements and satellite images from other spectral bands.

Introduction

In the comparatively mild winter climate of Britain, snow is irregular and intermittent, apart from higher parts of the Scottish Highlands, and has been a neglected part of the hydrological cycle. The occurrence of snow does, however, pose serious problems both in the evaluation of water resources and in the provision of flood defence. Part of the problem arises from the difficulty of measurement of both falling snow and snow cover. Standard raingauges are inadequate for measuring snowfall and no shielded gauges are used operationally. The network of snow water equivalent measurement stations is limited and there are problems of access when the information is most needed.

The National Rivers Authority of England and Wales (NRA) has contracted work to be done by the Remote Sensing Unit (RSU) of the University of Bristol on the remote sensing of snow by satellite, to improve understanding of snow hydrology and to provide better operational tools for management of water resources and flood defence (Bailey *et al.* 1993). The NRA is interested in evaluating both the potential, and practical and operational limitations of satellite remote sensing procedures and possible means of circumventing these limitations.

In this paper the satellite remote sensing of snow is placed in the context both, of the characteristics of the maritime snow climate which Britain experiences, and the hydrological problems which the climate imposes. The limitations, resulting from cloud cover, on satellite visible and near infra-red sensing of snow are assessed.

The Maritime Snow Climate of Britain

Unlike Alpine and continental parts of Europe, the maritime climate of Britain restricts the duration and persistence of snow cover. There are, however, wide variations in occurrence over the country and from year to year.

Manley (1939) gives details of average number of days with snow lying for the period 1912 to 1938 and the Meteorological office (1975) for 1941 to 1970, over Britain as a whole. There is an increase in average annual duration from south to north, from west to east and with increasing altitude. Thus the annual duration is only 1.5 days near sea level in the South west Peninsula, rising to 8 days in the London area. Over much of the Midlands, East Anglia and lowland parts of Northern England and Scotland, snow cover duration is in the range 10 to 20 days.

Jackson (1978) summarises the effects of altitude by deriving equations and graphs relating duration at a point to its elevation, and the sea level duration in that vicinity. Thus significant areas of the Pennines, Wales and Lake District and a larger proportion of hills in Scotland have average durations over 30 days. At the highest summit in Scotland, Ben Nevis (1,343 m) snow duration is over 200 days and at Cross Fell (898 m), the highest point in the Pennines, it is over 100 days (Manley 1971).

The snow cover does not persist continuously for the durations noted but may accumulate and melt completely several times during the course of a winter. The intermittent character of the snow cover is defined in Table 1 in terms of the number of snow spells (from accumulation to melt) per winter, the median duration of a spell, and the median longest spell duration in each year, at a number of locations in England and Wales. Thus at Catcleugh in the northern Pennines (Fig. 1) with an annual duration of 39 days, the median longest spell duration is 13.5 days and of all spells is only 6 days. Median spell duration decreases to 3 to 4 days for most lowland areas. Snow cover duration is of importance in influencing the chances of obtaining cloud free images from satellite.

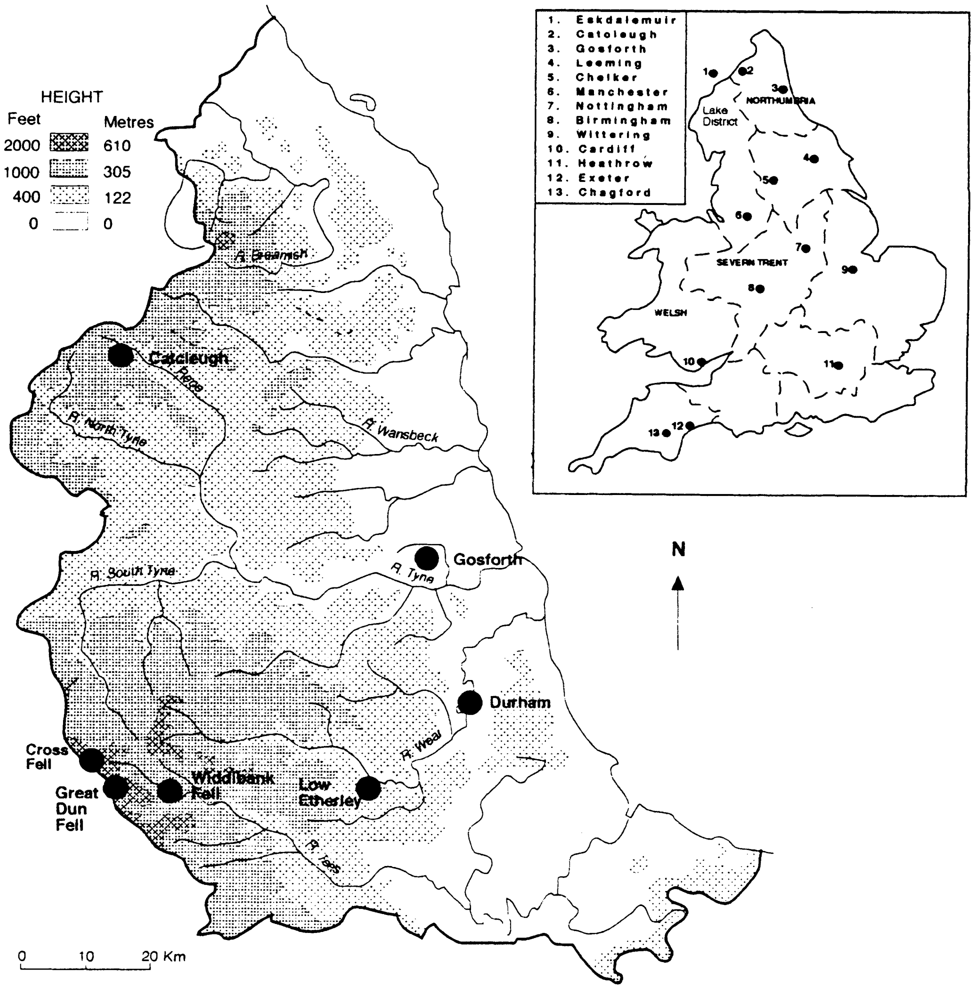

Fig. 1. The Northumbria region of the National Rivers Authority in Northeast England showing locations mentioned in the text.
1a) England and Wales showing NRA regions and measurement locations.

Table 1 – Snow spells at selected stations in England and Wales, 1954 to 1971

	Catcleugh N Pennines	Gosforth NE Lowlands	Chelker S Pennines	Evancoyd Welsh Hills	Chagford Dartmoor
Median annual duration	39 days	19	12	21	9
Median number of spells	6.5	5.0	3.0	5.0	3.5
Median spell length	6.0 days	3.8	4.0	4.2	2.6
Median longest spell	13.5 days	8.0	7.0	8.0	4.5

Snow occurrence is also characterised by wide variations in spatial extent, duration and depth from year to year. In more extreme years such as 1947, 1963 and 1979, snow may cover much of the country for several months (Douglas 1947; Shellard 1968). In mild winters lowland areas may experience only a few flakes which melt on reaching the ground. In virtually every part of the country snow has been over 40 cm deep at some time in the last 100 years except near some western coasts; in the uplands it may accumulate to well over 100 cm. Such totals may accumulate in a single storm, for example 107 cm in Durham in a 2 day storm in February 1941 and 76 cm in Cardiff in 1945 (Jackson 1978). Less information is available on water equivalent but Archer (1981) records amounts up to 200 mm in the Pennines in 1979 and Ferguson (1984) indicates values over 300 mm in several winters in the Scottish Highlands.

The Hydrological Implications of Snow in Britain

In contrast to its major impact on higher mountains in Europe and North America, snow in Britain is perceived by many water managers as an irritant rather than a major concern in the management of water resources and flood defence, in view of its sporadic and infrequent occurrence. It has however contributed to some of the most serious floods to have occurred in the country and it poses problems in water resources management and operation.

Amongst the statutory duties of the National Rivers Authority of England and Wales is that a "conserving, redistributing or otherwise augmenting water resources in England and Wales" and "securing proper use of water resources". Implicit in this duty is the need to monitor and measure water volumes and flows at various stages in the hydrological cycle insofar as they impact on water resources.

Imperfections in knowledge of precipitation inputs in the form of snow to catchments seriously limit the accuracy of rainfall runoff models especially in reservoired upland catchments where a significant proportion of winter precipitation may occur as snow. Modelling difficulties arise both in the assessment of the volume of input as snow fall and the timing of melt and contribution to runoff (Fleming 1970; Johnson and Archer 1973). These in turn may seriously influence the assessment of reliable yield of upland resources (Barton 1973).

Snow hydrology is, however, generally considered to be more important in Britain for flood defence than for water resources, both in the design of major structures and in the provision of flood warning systems for snowmelt floods.

In most years the melting of snow even from deep snowpacks in upland Britain occurs without serious flooding. However, in those years when a persistent snow cover extends to lowland Britain, its thaw is frequently accompanied by serious flooding as, for example, on the River Wansbeck in north east England in 1963 (Archer 1984), which was the largest flood on that catchment for at least 120 years.

More frequently flooding results from a combination of melting snow and rainfall as, for example, occurred on the Severn in January 1982, on the Yorkshire Ouse in 1982 and 1991, on the Tyne in 1955 and 1968 and the Tay in February 1990 and January 1993.

The recent flood on the River Tay in central Scotland illustrates typical characteristics of severe snowmelt flooding in Britain (Anderson and Black 1993).

Heavy snow showers and strong winds from 11 to 14 January 1993 resulted in large accumulations of drifted snow over the Tay and Earn catchments. By late evening of 14 January heavy rainfall and temperatures rising to 5°C saw the beginning of the thaw on lower ground. Overnight 60 mm of rain fell in the headwaters and the remaining snow became saturated as it absorbed this rainfall. Temperatures rose further on 16 January to 12°C and, with an additional 40 mm rainfall was sufficient to mobilise a rapid melt at higher levels throughout the catchment. Serious flooding of land and property occurred but particularly in Perth where historical sources indicated that the flood was the highest since February 1814.

Significant features of this event were the short duration from the beginning of accumulation to almost total melt, the large volume of combined rain and snow and the difficulty of obtaining realistic ground based measurements of snow with limited access in rapidly changing conditions.

Forecasting the magnitude and timing of such floods is difficult firstly because of inadequate knowledge of the volume of water lying as snow on the catchment at the onset and during the melt, and secondly with respect to the thaw, because of an incomplete understanding of the energy balance at the snow surface, liquid water retention in the pack and a dearth of meteorological measurements with which to make predictions.

In England and Wales the NRA has statutory powers to provide and operate flood warning systems. The NRA is concerned to improve the performance of snowmelt flood forecasting which at present relies mainly on monitoring the progress of flood wave from upstream to downstream gauging stations rather than from the rate of melt or depletion of the snowpack over the catchment.

Satellite Remote Sensing of Snow

Remote sensing by satellite was considered to have the potential to provide spatial data on a range of snow properties in real time both for water resources and flood warning purposes. The Remote Sensing Unit (RSU) of the University of Bristol has been contracted by the NRA to develop procedures and to assess the operational viability of snow remote sensing. This project builds on previous work by the RSU which concentrated on the development of algorithms to assess snow covered areas using data from AVHRR on the National Oceanic and Atmospheric (NOAA) meteorological satellites. These data, for visible and infrared wavelengths, provide imagery with a spatial resolution of approximately 1 km on the ground (Lucas 1990). That study included development of automated procedures for distinguishing between cloud cover and snow. The new study has:

1) Refined procedures for snow area assessment based on visible/infrared satellite image data.
2) Developed snow depth classifications based on visible satellite image data.
3) Considered techniques already available for snow water equivalent estimation based on passive microwave satellite imagery, and applied these to a number of cases.
4) Combined satellite and collateral data (in the form of a digital terrain model) for improved snow characterisation under areas of cloud cover.
5) Developed routines for monitoring snow field changes from day to day.
6) Assessed a range of strategies for possible operational implementation of some or all of the above.

The operational value of snow cover assessment by AVHRR imagery depends on the availability of cloud free localities in critical areas of the satellite images especially during periods of ablation, as a guide to the rate of melt and immediately prior to melt, as an indication of water equivalent available for runoff. The frequency and amount of cloud has been assessed both from ground based observations and from satellite analysis.

Winter Cloud Frequencies

A broad indication of winter cloud frequencies is provided by Laing and Grant (1980). This showed percentage frequencies in each class of cloud cover for each month of the year based on eight readings per day for all principal climate stations in the UK. An example is provided in Table 2 for Leeming, a lowland station in north east England.

Cloud is observed in oktas or eighths of the sky but further definition is required.

- 8 oktas is used only for fully overcast.
- 7 oktas is used when there are any breaks in the cloud however small. On average therefore 7 oktas represents not 87.5 % but more than 90 % cover.
- Sky obscured is used when there is a ground based cloud layer (fog). With respect to constraints on satellite sensing this may be grouped with 8 oktas.

Table 2 illustrates the predominance of the 7 and 8 oktas classes throughout the winter with 56 % to 62 % in those ranges and with a tendency to greater amounts in January and February the months with greater frequency of snow. With the inclu-

Table 2 – Percentage frequencies of cloud cover in each okta class during winter months for Leeming, Yorkshire. Location is shown in Fig. 1 (after Laing and Grant)

CLOUD COVER OKTAS	NOV	DEC	JAN	FEB	MAR	APR
0	7.3	7.0	6.8	6.3	7.3	5.0
1	10.0	9.0	8.5	7.9	7.2	8.1
2	5.0	4.8	4.7	4.3	4.6	4.4
3	4.7	4.3	4.2	4.2	3.9	4.5
4	3.1	3.0	2.7	2.8	3.2	3.4
5	4.0	4.0	4.0	3.8	4.3	5.0
6	5.8	6.9	5.9	6.2	7.3	8.0
7	21.4	23.0	21.2	21.6	24.3	26.9
8	33.1	31.7	36.4	38.5	35.5	33.3
Sky Obscured	5.6	6.2	5.6	4.4	2.5	1.4

Table 3 – Comparative percentages of cloud cover in the 7 and 8 okta classes between day (A) and night (B) during winter months at selected stations in England and Wales. Locations are shown in Fig. 1 (after Laing and Grant)

STATION	ALT	NOV	DEC	JAN	FEB	MAR	APR
Eskdalemuir	242 D	65.4	66.5	72.9	66.6	68.1	62.8
	N	56.9	59.9	67.9	62.5	59.7	51.7
Leeming	32 D	63.8	63.8	66.3	68.2	66.0	65.1
	N	58.0	59.8	61.7	62.0	58.6	56.7
Wittering	73 D	62.7	64.3	67.6	69.3	61.7	61.2
	N	55.0	59.5	63.3	62.1	55.2	53.6
Nottingham	117 D	63.9	64.9	68.0	69.4	62.2	62.4
	N	57.3	62.3	64.4	62.8	56.3	53.4
Birmingham	96 D	65.1	67.3	71.1	71.5	64.4	64.0
	N	58.8	63.7	67.2	63.9	56.0	55.0
Heathrow	25 D	64.9	68.2	70.8	68.9	59.8	57.5
	N	56.9	62.7	67.0	63.5	54.0	50.2
Exeter	32 D	64.8	66.0	73.4	67.2	60.7	56.6
	N	58.2	63.6	65.7	63.7	57.9	47.8
Manchester	75 D	64.1	64.8	68.3	65.5	61.3	60.1
	N	57.9	64.3	65.5	61.8	56.1	54.1

sion of the 6 okta class, the frequency through the winter rises to 64% to 68%. These ranges are typical for most of the lowland stations listed.

It is only during daylight hours that AVHRR visible and infra-red sensors can be used to assess snow cover, and both are required for dependable snow/cloud discrimination. In a further analysis Laing and Grant (1980) show how the frequency of snow cover varies between day and night hours. Cloud cover in the 7 to 8 okta classes for day and night observations is compared in Table 3 for several stations in England and Wales. These show that the frequency of winter cloud cover in these classes is about 5 % higher during the day than during the night.

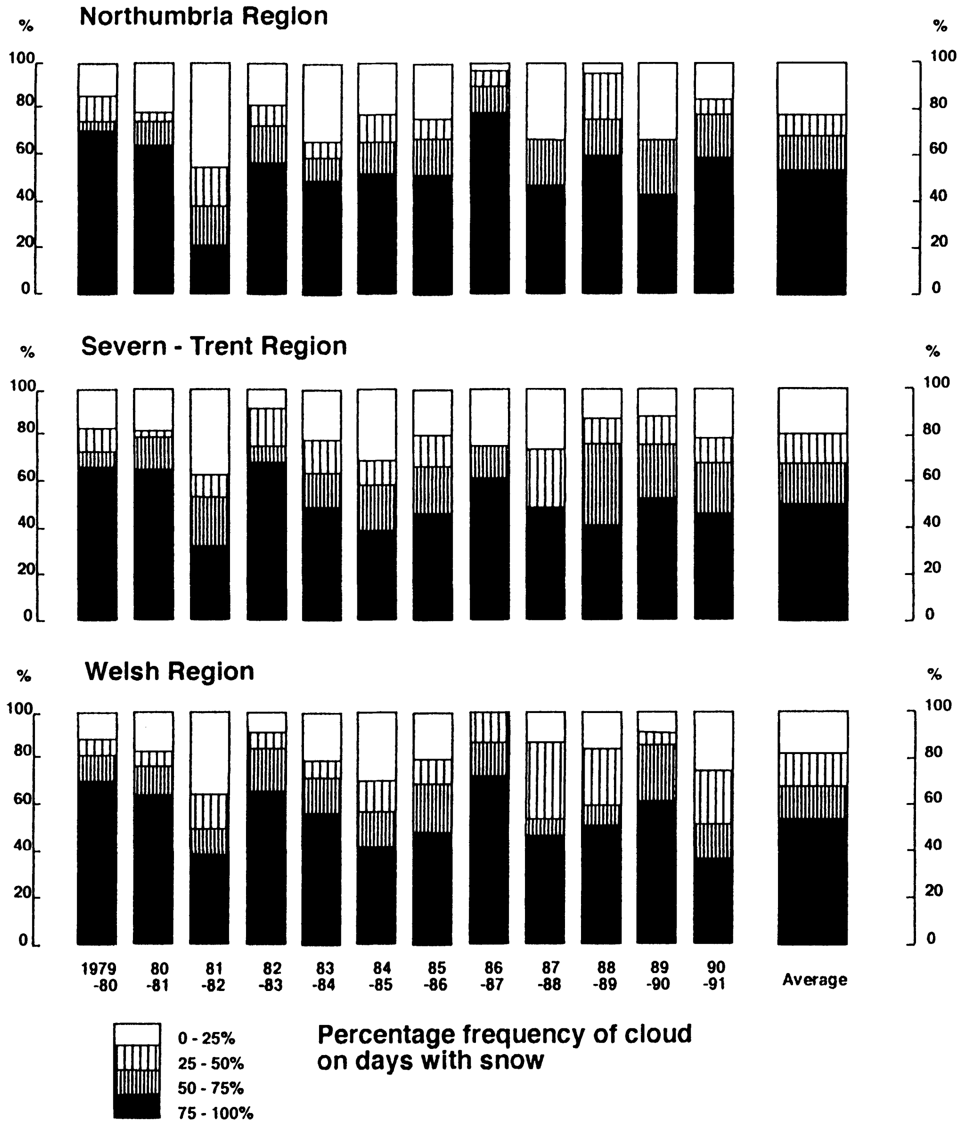

Fig. 2. Frequency of cloud cover on days with snow based on visual inspection of satellite images for three NRA regions of England and Wales (Figure based on Greenhill *et al.* 1992).

Cloud Cover in Association with Snow – Satellite Analysis

The analysis of Laing and Grant refers to periods with and without snow cover, which may differ in their cloud cover frequency. As a first step in assessing cloud cover frequency in periods with snow, satellite AVHRR hard copy images in the archive at the University of Dundee Satellite Receiving Station were examined visually for the period 1979 to 1991 using the categories proposed by Djavadi and Cracknell (1986), namely 0-25, 26-50, 51-75 and 76-100 per cent cloud cover. Daily evaluations were made for all winter snow days over three NRA Regions, Northumbria, Severn Trent and Welsh, and over England and Wales as a whole (Fig. 1a). Results of this study were reported by Greenhill *et al.* (1992), and give a more optimistic view of possible cloud cover constraints on the potential usefulness of satellite monitoring of snow than those based on surface assessment of cloud alone (Fig. 2).

Table 4 presents the statistics resulting from this study for the three regions selected, and for the whole of England and Wales. Table 5 gives values for England and Wales as a whole for the three conditions of accumulating, stable and melting snow, the snow state being assessed from ground-based measurements. Case

Table 4 – Annual percentage of snow days with different cloud cover amounts (cloud cover expressed as percentage) from visual satellite image analysis for three regions of the National Rivers Authority (from Greenhill *et al.* 1992)

Date	National Rivers Authority Welsh Region						Severn Trent Region					
	cloud cover (%)				% snow visible		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

Note: Samples have been taken on snow days reported from ground-based sources. The percentages of YES/NO snow indicate whether snow is visible or not on the hard copy images.

cont..

Table 4 – Annual percentage of snow days with different cloud cover amounts (cloud cover expressed as percentage) cont.

Date	Northumbria Region						England and Wales					
	cloud cover (%)				% snow visible		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 on snow days reported from ground-based sources. The percentages of YES/NO snow indicate whether snow is visible or not on the hard copy images.

Table 5 – Yearly average percentage of snow days with different levels of cloud cover under different phases for England and Wales (from Greenhill *et al.* 1992)

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

studies undertaken during the RSU Bristol project suggested that useful assessments of snow on the ground could be made under cloud cover conditions of 75 % and less, depending on the particular spatial distributions of the snow and the cloud. Thus it can be concluded that at least 50 % of the winter AVHRR images inspected could be used to provide valuable information on snow conditions over some part(s) of the regions concerned.

In the areas considered, dense cloud and fog (> 75 % cover) was most frequent in Northumbria and least in Severn Trent with 54 % and 48 % dense cloud and fog in either region respectively.

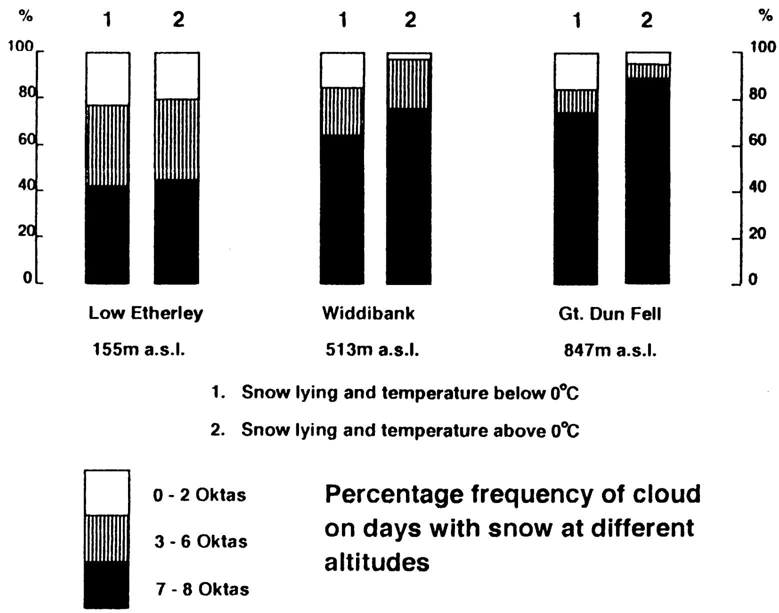

Fig. 3. Frequency of cloud cover on days with snow, with concurrent temperatures at 0900, above or below 0°C, for stations at different elevations in Northeast England.

Cloud Cover in Association with Snow – Ground Based Analysis

The visual satellite analysis as conducted above was unable to distinguish between periods of snow accumulation, stability and melt, the last being of the greatest interest for flood warning. Ground based data were used to distinguish cloud cover between periods with snow cover and temperatures above and below 0°C. Results from Greenhill *et al.* (1992) are shown in Fig. 3 for three stations in north east England, Low Etherley, Widdibank Fell, and Great Dun Fell, whose locations are shown in Fig. 1. At each of these sites cloud cover is greater during periods of ablation than with temperature below 0°C, differences ranging between 5 and 15%.

The study of the three individual stations also showed a clear relationship between cloud cover and altitude, with the highest station Great Dun Fell (847 m) offering the least opportunity for direct observations of the snow field in its immediate vicinity with 89% of cases attaining 7 or 8 okta cloud or fog with associated temperatures above zero, and 74% of cases in this category when temperatures were below zero.

Certainly there is a potential problem in using regional cloud cover based on satellite analysis in Great Britain in that those areas with greatest snow cover, and which are the greatest natural contributors to snowmelt flooding, may be the most persistently cloudy. In the Northumbria region, average snow cover duration increases from 8 days per year on the coast to 40 days at 300 metres to more than 60 days on Pennine summits. On the other hand, the greatest floods occur when melt is occurring over entire catchments, and in these circumstances there is a higher probability of the satellite techniques being able to make a valuable contribution to the assessment of the flood potential.

Conclusions

Cloud clearly imposes serious constraints on the use of AVHRR sensing of snow areas and properties. Given the typically short duration of snow cover, it is likely that on some occasions no images will be available at the catchment scale from the beginning of accumulation to completion of melt.

During periods of rapid melt when a view of the changing snow cover would be most helpful, the chance of obtaining sequential cloud free images is very low, but useful assessments can be made from partially cloudy scenes.

In consequence of the above, satellite sensing which depends on visible and infra-red images can not be regarded as the prime basis for snow cover assessment in Britain. It can however provide helpful ancillary data in support of ground based measurements and of satellite images from other spectral bands, which are not so limited by cloud cover.

To overcome or mitigate these difficulties the NRA/RSU project has directed attention to three additional lines of enquiry:

1) The use of snow cover evidence from visible and infrared sensors even when spatially and temporally discontinuous, to help construct broader area pictures of snow conditions.
2) The use of terrain and vegetation information organised in a suitable Geographical Information System to help infer snow conditions under cloud from nearby cloud free areas.
3) The use of imagery from cloud-penetrating passive microwave sensors for assessment of snow area, depth and water equivalent in cloudy conditions. Although this imagery is of lower spatial resolution than visible and infrared imagery, techniques based on passive microwave data are showing potential in those regards.

These three topics will be the subjects of further publications on snow monitoring improvements in Great Britain resulting from the NRA/RSU study.

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First version received: August, 1993
Revised version received: 20 November, 1993
Accepted: 21 December, 1993

Address:
D.R. Archer,
National Rivers Authority,
Northumbria and Yorkshire Region,
Eldon House, Regent Centre,
Gosforth, Newcastle upon Tyne, Ne3, 3UD, GB.

J.O. Bailey, E.C. Barrett and D. Greenhill,
Remote Sensing Unit, Dept. of Geography,
University of Bristol,
Bristol, BX8, 1SS, GB.