Interim Report R&D Project 207

Development of AVHRR/GIS Methodology for Snow Area/Depth Monitoring

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DEVELOPMENT OF AVHRR/GIS METHODOLOGY FOR SNOW AREA/DEPTH MONITORING

by

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1. INTRODUCTION

1.1 Objectives and background

1.1.1 Objectives

This Interim Report aims to reflect progress made during the Second Phase of the NRA/RSU study on satellite monitoring of snow, with special reference to the potential of National Oceanic and Atmospheric Administration (NOAA) satellite High Resolution Picture Transmission (HRPT) data in conjunction with Geographic Information Systems (GIS) to determine key characteristics of snow cover and to improve existing monitoring routine for the same.

The specific objectives are:

(1) To assess the potential of satellite remote sensing for the determination of snow area/depth, identifying accuracy and spatial and temporal resolution under different snow conditions and terrain (surface morphology and vegetation).

(2) To develop and test procedures for measurement of snow depth by satellite remote sensing using snow survey report published by the UK Meteorological Office and snow survey carried out by local NRA as ground truth data in areas selected from Northumbria, South Pennines and South Wales.

(3) To improve the present monitoring of snow area using BRISCA (Bristol Ice and Snow Cover Algorithm), especially in relation to estimation beneath persistent clouds.

(4) To explore and to demonstrate the use of GIS in supplying ancillary data (e.g. incorporation of ground data) required in imagery analysis and in extending the validity of information from remote sensing data.

1.1.2 Background

The work addressed in this Report is a continuation of the NRA project entitled "Remote Sensing of Snow by Satellites" (See also Bailey *et al.* 1991; Greenhill *et al.* 1992; and Beaumont *et al.* 1992). Seven objectives have been proposed for Phase II of the project. This Interim Report reflects work done to meet the requirement for achieving one of the seven objectives, i.e., development of snow area/depth monitoring using NOAA Advanced Very High Resolution Radiometer (AVHRR) HRPT data and GIS methods. The focus of the project at Stage II has been on the analysis of the influence of age, extent and condition of the snowpack by studying the satellite signals from sequential NOAA AVHRR images during periods of snow accumulation, stability and ablation for snow events during 1990/91. Analysis on the influence of terrain and vegetation is also attempted primarily by reference to more detailed information on selected basins for which customised GIS data bases are configured and used. The areas for this purpose have been selected in Northumbria and South Wales based upon the availability of different data sets for snow study. Ground-based snow information has been obtained from the relevant NRA region for comparison with satellite imagery. Other proposed areas in South Pennines and Severn Trent regions were not used for study of snow events during 1990/91 because of the lack of cloud free satellite data for snow events during this mild winter.

1.2 Context to the present study

The nature of snow cover distribution is governed not only by atmospheric processes at the time of snowfall, and during the period of snow lay, but also by terrestrial influences which modify atmospheric conditions and directly affect the variability of snow cover. Both atmospheric and terrestrial controls are integrally related and cannot be considered independently.

Air temperature controls the dryness, hardness and crystalline form of snow on the ground and hence its subsequent erodability by wind. Redistribution of snow by turbulent wind flow near the ground can change snow density through the alteration of its physical structure. Terrestrial influences on snow cover include local *in situ* vegetation, physiography, elevation and slope which all combine to continually modify energy and moisture transfers within the snowpack. A chosen methodology of snow cover measurement must be adopted primarily with respect to scale and secondly with respect to those factors influencing energy and moisture transfers within a snowpack.

Traditional point measurement techniques used at a meso-scale (10^2 - 10^4 m) or macro-scale (> 10^4 m) are logistically difficult to implement in the field and lack of representative observations over a wide area can lead to inaccurate estimates of total water equivalence. It is in this respect that satellite remote sensing may provide invaluable information for measuring snow cover over large areas.

This Report is concerned with the improvement on the techniques involved in developing the Bristol operational snow monitoring algorithm using AVHRR data in conjunction with GIS for supplementation of satellite image techniques.

At an early stage of work for Phase II, a preview meeting was held at the Remote Sensing Unit, University of Bristol, to identify opportunities and the NRA needs for operational snow cover monitoring by satellites. Representatives from different NRA regions attended the meeting. Most of them showed interest in remote sensing of snow by satellites, though differing on its urgency, frequency and priority. Currently many NRA regions have micro-based computer systems for field data collection and analysis. Models from weather radar data are widely used at 5 km^2 resolution. For those regions where the worst flood runoff event is often contributed by snow melt rather than rainfall (e.g., Northumbria and Yorkshire), data on snow depth and density are mainly collected by volunteers for a few selected stations. But the unreliability can be questionable as rarely specialised/trained expertise is involved. Also, the insufficiency of point data is obvious. Therefore, external data sources are sought for improved monitoring of major snow events.

In the meeting, it was stressed that efforts should be made to integrate remote sensing and GIS to establish the relationship between water quality and snow melt, and to explore the potential of incorporating radar data for infiltration improvement from snow modelling. Also, requirements on the assessment of the total cost, time-consuming and the importance of providing near-real-time snow area, depth and water equivalent were put forward. Other suggestions were made concerning matters such as assessment of the melting layers or maximum melting rate. The importance of the incorporation of ground data was also stressed.

In order to meet different operational requirements, a combination of different data sources is needed, especially since cloud cover constitutes a constraint on the utilisation of AVHRR data (Greenhill *et al.* 1992).

This Report is divided into the following sections to present progress made during Phase II:

data acquisition;
pre-processing;
snow area mapping;
snow depth estimation;
the use of GIS.

Conclusions and recommendations are made at the end of the report in view of the needs and prospects for future work.

2. DATA ACQUISITION AND PRE-PROCESSING

2.1 NOAA AVHRR images

2.1.1 Data acquisition

Following the previous Bristol studies on snow monitoring (Lucas and Harrison 1989; Bailey *et al.* 1991), AVHRR data from NOAA satellites remain the primary data source in the continued development and improvement of snow area/depth monitoring. The daily availability, easy access, low cost and wide coverage of AVHRR data are continuously appreciated for an operational and consistent snow study of the UK. Table 2.1 presents different NOAA AVHRR bands and their spectral locations.

Table 2.1 NOAA AVHRR bands and spectral characteristics

Band	Wavelength (μm)	Nominal spectral location
1	0.56-0.72	Green
2	0.71-0.98	Near Infrared
3	3.53-3.94	Infrared
4	10.32-11.36	Thermal Infrared
5	11.45-12.42	Thermal Infrared

Thirty-six images from NOAA-9, NOAA-10, NOAA-11 and NOAA-12 satellites, covering the period from 8 December 1990 to 24 February 1991, have been obtained for the three major snow events in England and Wales during winter 1990/91. These were used in developing and testing refined procedures for snow depth monitoring with improved facility and efficiency.

AVHRR images for the period from 17 December to 23 December 1991 were also obtained and processed in regard to the snow event during 20 December 1991 to 24 December 1991 in Northumbria NRA region which might have contributed to the local flood at the time. Unfortunately these images are largely cloud covered and are of little use for this purpose. Table 2.2 lists the NOAA AVHRR data newly acquired for snow events during 1990/91.

2.1.2 Image pre-processing

While following the basic procedures for NOAA AVHRR data pre-processing as described in the previous Interim Report (Bailey *et al.* 1991), a series of programs for calibration and navigation of AVHRR data have been updated and improved to give an increased efficiency and flexibility in accordance with the recently available facilities in the Remote Sensing Unit (RSU) in the University of Bristol. These form useful contributions to the future systematic and operational implementations of the snow monitoring algorithms.

Figure 2.1 shows several steps taken for AVHRR data pre-processing. First of all, the program "**DUNDEE_AVHRR**" unpacks the NOAA data from the 10-bit records of Dundee formatted computer compatible tape into a video file, which contains a 16-bit, five band raw data image. The video image is then calibrated using "**CALIBRATE_ALL**" program

Table 2.2 List of acquired AVHRR images from Dundee HRPT satellite receiving station

Tape ID	Date	Eqx. °West[a]	Eqx Time[b]	Satellite Number
917/02B	08/12/90	333.01	12:29:04	11
917/05B	09/12/90	355.69	13:59:52	11
923/10B	09/01/91	344.25	13:16:15	11
923/13B	10/01/91	341.41	13:04:58	11
924/02B	11/01/91	338.56	12:53:38	11
924/05B	12/01/91	335.71	12:42:22	11
924/07B	13/01/91	184.56	06:22:09	9
924/08B	13/01/91	332.87	12:31:03	11
924/09A	13/01/91	358.38	14:13:06	11
924/10B	14/01/91	181.45	06:09:55	9
924/11A	14/01/91	330.02	12:19:44	11
924/11B	14/01/91	355.53	14:01:48	11
924/13B	15/01/91	178.35	05:57:41	9
924/14A	15/01/91	327.17	12:08:26	11
924/14B	15/01/91	352.68	13:50:29	11
925/02A	16/01/91	199.08	08:32:40	10
925/02B	16/01/91	324.32	11:57:06	11
925/03A	16/01/91	349.83	13:39:09	11
929/04B	06/02/91	177.98	07:07:16	10
930/01B	10/02/91	179.95	07:15:02	10
930/02A	10/02/91	329.60	12:20:04	11
930/02B	10/02/91	355.11	14:02:07	11
930/04A	11/02/91	199.41	08:32:50	10
930/05A	11/02/91	352.25	13:50:45	11
930/10A	13/02/91	346.53	13:28:03	11
931/04A	16/02/91	337.95	12:53:56	11
931/05B	17/02/91	189.70	07:53:48	10
931/06B	17/02/91	335.09	12:42:35	11
931/07A	17/02/91	0.60	14:24:39	11
931/11B	19/02/91	329.36	12:19:52	11
931/12A	19/02/91	354.88	14:01:55	11
931/14B	20/02/91	352.01	13:50:32	11
932/03A	21/02/91	349.15	13:39:11	11
932/05B	22/02/91	346.29	13:27:48	11
932/08B	23/02/91	343.42	13:16:23	11
932/11A	24/02/91	340.56	13:05:03	11
1109/14	17/12/91	337.94	13:21:03	11
1110/02	18/12/91	181.94	02:57:04	11
1110/09	19/12/91	182.98	07:44:35	12
1111/04	20/12/91	354.48	14:27:22	11
1111/09	21/12/91	351.48	14:15:29	11
1111/14	22/12/91	348.48	14:03:35	11
1112/05	23/12/91	345.48	13:51:41	11

Note: a. Equatorial crossing angle expressed as degrees West
b. Equatorial crossing time (GMT).

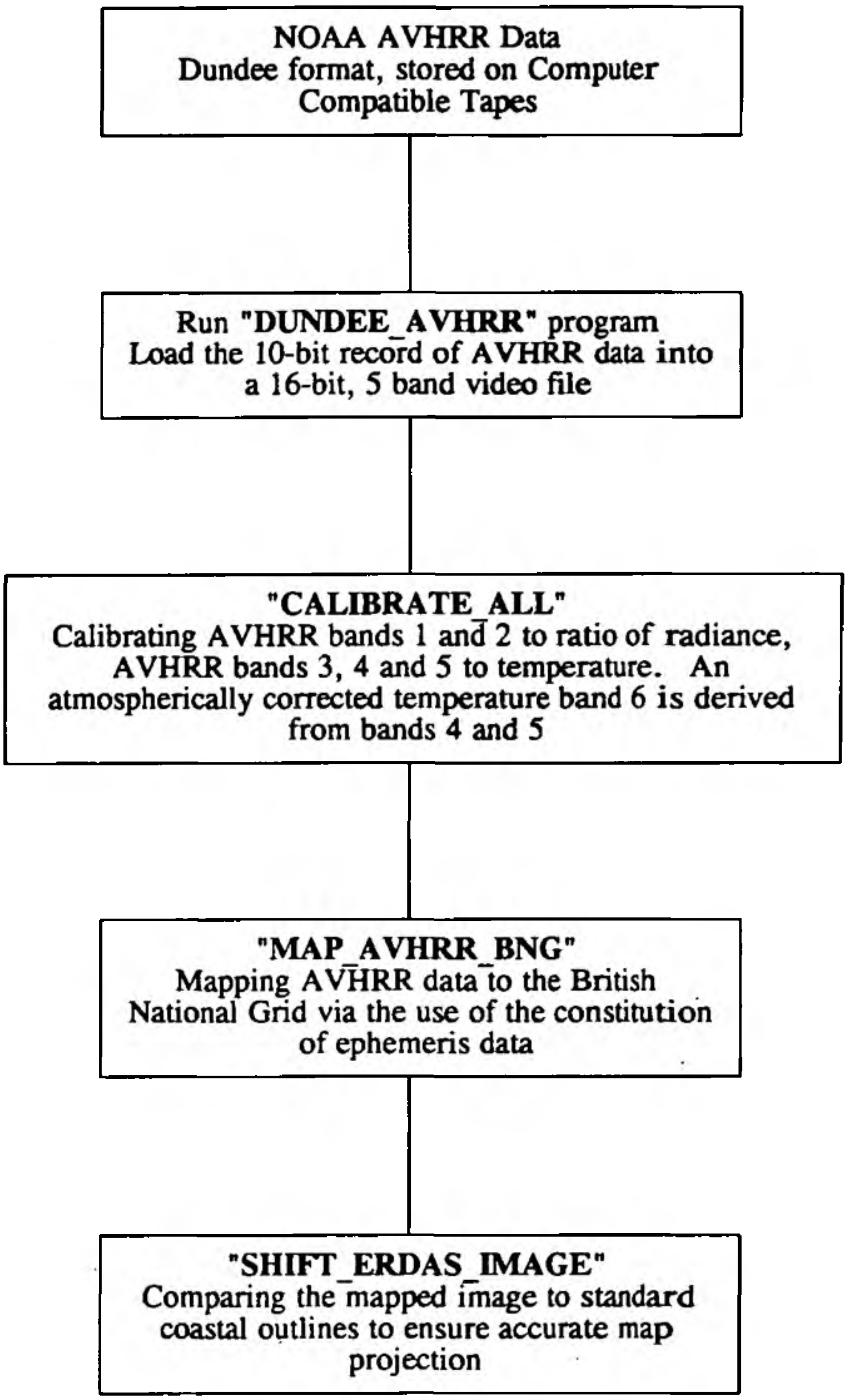


Figure 2.1 Procedures for NOAA AVHRR data pre-processing

to a 16-bit, six band image, with band 1 and band 2 calibrated to ratio of radiance, bands 3, 4 and 5 calibrated to temperature either in Kelvin or Celsius scale. A minimum temperature needs to be input for calibration of the thermal temperature bands 3, 4 and 5 if output in °C is requested. A minimum temperature of -20°C has been used to counter most of the variations in the thermal bands for snow study except some very cold clouds with temperature below -20°C. Band 6 is an atmospherically-corrected temperature band derived from a comparison of the calibrated band 4 and band 5. The spectrally calibrated data were then mapped and registered into British National Grid by using the constitution of ephemeris data supplying information on orbital parameters. This mapping exercise is performed by running the program **"MAP_AVHRR_BNG"**, where the required input data are the equatorial crossing time and the equatorial crossing angle expressed as degrees West. The output area of the mapping image is defined by the top left corner coordinates in the National Grid, along with the required pixel size and image size. The geometry of the mapped images can be further examined and shifted to ensure accurate registration to the standard coastal outlines.

The available images are processed and registered to British National Grid using updated programs. Since the ERDAS system available in the RSU, University of Bristol, can now handle 16-bit data directly, an albedo scaling of 10 and a minimum temperature threshold of -20°C have been used for the calibration of NOAA AVHRR images.

2.2 Landsat Thematic Mapper (TM) data

The fine spatial resolution (30 m x 30 m) of TM data offers a means for a detailed study of snow area mapping and assessment of snow depth. Classification of TM images and identification of snow areas can be used to measure the performance of NOAA AVHRR image analysis.

To date, the TM data acquired and used in the project include: two quarter scenes of South Wales with snow on the ground for 27 February 1986 (203/24, Quarter 1 and Quarter 3); one quarter scene of Northumbria without snow on the ground for 20 November 1987 (204/22, Quarter 2); and one quarter scene of Northumbria with snow on the ground for 15 January 1991 (204/22, Quarter 2). In general, the TM images are of good spectral quality. In order to keep the spectral consistency of the data, classifications of TM images were carried out without pre-processing. The spatial distortions of the TM images were eliminated by the geometric correction and resampling of images. The resultant image coordinates are also registered to the National Grid reference. The newly acquired TM image of Northumbria for 15 January 1991 has been used to evaluate the performance of NOAA AVHRR image under different snow and terrain conditions than those inspected in Stage I.

2.3 Other data used

There are four components currently being incorporated into a GIS data base which assist satellite imagery analysis: topography, vegetation cover, courses of rivers draining the local areas and ground survey data on snow depth and density. Field observations of snow depth are the primary data used to verify the snow depth products of the algorithm. Topography and vegetation cover information assist estimation of snow depth variation on a catchment and regional scale. They are also used to complement the algorithm for prediction of snow cover extent beneath clouds which both TM and AVHRR sensors fail to tell directly.

Vegetational influences on snow cover are analysed through the use of digitised forestry areas and Landsat TM image classification. Coverage of forestry areas in Northumbrian region has been digitised from the Ordnance Survey 1:250 000 maps and stored as a GIS file to be incorporated in the imagery analysis. It covers an area of 130 km x 170 km from the National Grid reference 350 000, 660 000 to 480 000, 490 000. The use of this coverage will be detailed in Section 5.

Topographic components of the data base include elevation, aspect, slope, catchment boundaries and river courses. Elevation, aspect and slope variations for both Northumbria and South Wales have been analysed using Digital Terrain Models (DTM) for these regions. Two forms have already been implemented:

(a) An RSU-generated DTM for Northumbria; and
(b) An Ordnance Survey-produced DTM for South Wales.

The RSU DTM was produced by digitising at 50 m contour intervals and storing the files in 16-bit ASCII format. Digitised files were transferred across the Ethernet to the SUN/SPARC network where Fortran 77 software registered each file to the National Grid reference (program "**GINGA_TO_DEM**"). A file was then generated, by concatenating each sub-file using SUN software to produce on large file containing the digitised points for the whole area. Conversion of point ASCII data to an ERDAS raster image file was achieved using the RSU interpolation software "**CONTOUR**". Pixel size was set to 50 m x 50 m producing an image size of 1200 x 1200 pixels, with an areal coverage of 60 km x 60 km square from the National Grid reference 360 000, 580 000 to 420 000, 520 000. As the resultant DTM is registered to the National Grid, it can be clipped to any defined area using the ERDAS "**SUBSET**" function in order to produce coincidence between TM and DTM images. It is then possible to undertake quantitative comparisons between both image types by overlaying one with the other.

The Ordnance Survey of Great Britain is in the process of producing digitised DTM files of the UK from its 1:50 000 Landranger Map series. Since it has not completed the digitisation of Northumbbria at the time of study, the RSU had to undertake the task. However, DTMs of South Wales are available and nine tiles (one tile is a 20 km x 20 km square) were purchased covering a 60 km x 60 km square from the National Grid reference 260 000, 240 000 to 320 000, 180 000.

Each Ordnance Survey DTM tile is packed in ASCII format in one large headed file on computer compatible tape. Thus, when down loading the tape onto the SUN/SPARC network, the UNIX command "**dd**" has to include an unblocking sub-command to place "hard returns" at the end of each 80 character block. An RSU acquired Fortran 77 software package "**osdtm**" converts the large file containing a header and nine ASCII data files into nine single ERDAS raster image files each comprising one file of 50 m x 50 m pixel size. The nine files are then "stitched" together using the ERDAS "**LDDATA**" function. Since the Ordnance Survey DTM data are registered to the National Grid, navigation is not necessary.

Plates showing both the RSU generated DTM for Northumbria and the DTM of South Wales generated using Ordnance Survey digital data can be found in the Report by Bailey et al (1991: Plate 4.2 and Plate 4.3).

Also, for both regions, river courses and river catchment boundaries were digitised in the RSU in order to produce overlays for use with imagery analysis (e.g. Plate 4.4 in Bailey *et al.* 1991). The same method for digitisation was used as in the processing of the RSU DTM except that the program "**draw_map**" was used to produce the overlay in place of interpolation software. This also applies to the digitisation of the NRA regional boundaries and forestry areas in Northumbria, which will be further addressed in Section 5.

3. SNOW AREA MAPPING

3.1 Introduction

In order to examine the potential of satellite imagery for the assessment of snow depth, continued development and improvement of snow area mapping need to be performed first. In principle, the method used in this project is based on the semi-supervised multi-spectral classification of NOAA AVHRR imagery (Lucas and Harrison 1989). However, recently improved facilities in the RSU have enabled the process of image classification and snow area mapping to be carried out more efficiently while maintaining the classification accuracy. Meanwhile, methods of imagery classification and snow mapping have been progressively refined and simplified to meet the needs for operational implementation. The algorithm for snow area/depth monitoring has been progressively refined in terms of simplified procedure and increased efficiency to meet the requirement of its operational implementation. NDVI has been systematically deployed in the image analysis to differentiate marginal snow and cloud shadows, complete snow and partial snow areas.

Moreover, the establishment of a standardised data base with results registered to the National Grid reference allows the generation of subsequent thematic overlays for any selected area. For example, a snow depth study on a selected catchment or NRA region can be conveniently defined. Also, comparison of AVHRR and TM imagery analysis can be performed quantitatively and spatially.

3.2 Classification of NOAA AVHRR images

Calibrated and mapped AVHRR bands 1, 3 and 4 were used in the unsupervised classification using the Iterative Self-Organising Data Analysis Technique (ISODATA). The ISODATA uses the minimum spectral distance to assign a cluster for each candidate pixel. It begins with a specified number of arbitrary cluster means and then processed repetitively, so that these arbitrary means shift to the means of clusters in the data. The required inputs for running the ISODATA process are the number of clusters in the output file, the convergence threshold which is the maximum percentage of unchanged pixels reached between two iterations, and the maximum iteration which is the maximum number of times that ISODATA should recluster the data and prevents ISODATA from running too long or from potentially getting "stuck" in a cycle without reaching the convergence threshold. Careful choice of these inputs can save time in image processing while maintaining the quality of the statistical clustering. In this study, 40 clusters have been defined for most images' clustering. Maximum iteration is usually set at 120. In order to keep the ISODATA process within a limited time period acceptable for operational use, convergence threshold level has been reduced from 99.999% to 99.9%. A comparison has been made between TM image classification and AVHRR snow classifications using the convergence threshold of 99.999% and 99.9% respectively for 15 January 1991 (see Table 3.1 and Table 3.2). Similar results have been achieved but Table 3.1 shows results obtained using less time, and with increased efficiency.

The statistically clustered data, i.e., the resulting signatures of ISODATA, were further classified using Maximum Likelihood Classification. The required information classes such as snow areas and clouds can then be identified and assigned by examining the spectral signature and the spatial distribution of each cluster.

The principle behind the classification to distinguish snow from cloud cover and to define the snow area is that AVHRR band 3 and band 4 are primarily the snow/cloud discrimination channels while AVHRR band 1 describes the snowpack (Lucas and Harrison

Table 3.1 Number of pixels in TM and AVHRR snow classifications

AVHRR TM	Snow	No-snow	Total
Snow	685090	122060	807150
No-snow	54205	578645	632850
Total	739295	700705	1440000

Note: AVHRR classification achieved with convergence threshold level of 99.9%. The overall agreement is 87.8%.

Table 3.2 Number of pixels in TM and AVHRR snow classifications

AVHRR TM	Snow	No-snow	Total
Snow	596099	37381	633480
No-snow	143196	663324	806520
Total	739295	700705	1440000

Note: AVHRR classification achieved with convergence threshold level of 99.999%. The overall agreement with the TM image classification is 87.5%.

1989). The overlap in the spectral response of snow and cloud is characteristic of AVHRR band 1, but the spectral reflectance of cloud is much higher in calibrated AVHRR band 3 compared to the calibrated AVHRR band 4. This is because AVHRR band 3 at 3.53 - 3.94 μm is comprised of both reflectance and emission. That is, AVHRR band 3 measurement includes solar reflection and thermal emission. The solar reflection part can be roughly approximated by the T3.7μm - T11μm brightness temperature difference (i.e., AVHRR band-3 - band-4). Clouds are very reflective but the cold temperature makes them much less emissive. Also, snow covers are poor reflectors of sunlight at band 3 while clouds were relatively good reflectors at 3.53 - 3.94 μm. The upper parts of ice clouds are more efficient in scattering than a snow cover. The snow covers, in addition to having larger particles, also tend to have a much larger absorbing mass than the ice clouds.

Thus the acquired AVHRR images have been classified as snow, clouds and others (including land and ocean). The unsupervised multi-spectral cluster algorithm was considered to have shown the great potential for snow detection. For one snow occasion, a series of images covering successive dates are usually obtained. In this case, training data can be derived from classifications which demonstrates high levels of snow/cloud discrimination and minimal variation in class area when clustering. That is, statistics generated from one AVHRR image are used for another image classification. This is also called hybrid or semi-supervised classification. The advantage of the process mainly exists in reducing processing time but introduces no marked improvements in snow area detection.

The semi-supervised classification played the role of introducing cluster statistics into new classifications. These cluster statistics can be viewed as being similar to the training data required by supervised classification algorithms. The assignment of these clusters after the maximum likelihood classification was double-checked following the examination of the spectral signatures and the spatial distribution of each cluster.

3.3 Use of Normalised Difference Vegetation Index (NDVI)

3.3.1 NDVI and its calculation

As described in Section 2.1, the acquired AVHRR Channel 1 and Channel 2 data were converted to albedo (i.e. percentage ratio of radiance) and were multiplied by 10 to rescale them up to 16 bits. The NDVI was then calculated from the AVHRR band 1 and band 2 for each image. The NDVI for this study was expressed as follows:

$$\mathrm{NDVI} = \frac{\text{Near Infrared}}{\text{Near Infrared + Visible}}$$

i.e.

$$\mathrm{NDVI} = \frac{\text{AVHRR 2}}{\text{AVHRR 2 + AVHRR 1}}$$

A scaling factor of 100 was applied to rescale the output NDVI within the range of 0 to 100. Therefore the actual expression for the use of ERDAS "**ALGEBRA**" function in image processing algorithm was:

100 * X2 / (X1 + X2)

where X2 is the image file for AVHRR Near Infrared band 2 and X1 is the image file for AVHRR Visible band 1.

An output image file can then be produced containing the NDVI values for each pixel.

3.3.2 Description of snowpack

Contamination of the snow surface by particles (e.g. dust) influences visible snow reflectance while the near infrared wavelengths are more sensitive to grain size. These snowpack parameters can be derived with more confidence where a complete snow cover exists as, where vegetation, bare rock, soil or water contribute to AVHRR pixel intensity, the inter-relationships of visible and near-infrared brightness to snow pack parameters become extremely complex (Lucas 1989).

NDVI has been applied for the description of snowpack into partial or complete snow areas. Because land reflectance is usually higher in the near infrared than in the visible, NDVI is used to describe the percentage snow cover within a 1 km^2 AVHRR pixel. If the pixel is dominated by near infrared other than visible reflectance, it is assumed that less than 50 per cent of the pixel area is covered by snow and thus it is assigned as partial snow area. If the pixel has higher reflectance on visible band than near infrared, the pixel is assessed with more than 50 per cent of snow over the entire pixel area and then is assigned to the complete snow category. The discrimination process between partial and complete snow is carried out only on those clusters which have been identified as snow in the first place. This is done by masking the NDVI image file with snow areas alone and then recoding all the pixels with NDVI less than 50 as sample snow and NDVI equal or greater than 50 as partial snow. This newly produced GIS file through recoding was then overlaid with the classified snow file and replace the one snow class with two different snow classes, i.e., partial and complete snow.

3.3.3 Detection of low cloud/cloud shadows

The visible or near infrared test is useful to detect low clouds. The reflectance measured over the oceans corresponds to Rayleigh and aerosol scattering which is weaker in the near infrared than in the visible. The near infrared channel is more efficient to detect clouds over the ocean. The land reflectance is usually much higher in the near infrared than in the visible, due to the vegetation spectral radiative behaviour.

In this study, NDVI has been used to detect low cloud/cloud shadows and to discriminate between complete and partial snow. Some clusters are a mixture of low cloud and cloud shadows, especially including some low clouds over oceans which are difficult to be identified by the T3.7μm - T11μm brightness temperature difference. This is because Rayleigh scattering is more important at 0.6μm than at 0.9μm and is almost negligible at 3.7μm. Therefore, shadows of high clouds over low clouds give no solar reflection at 3.7μm, but relatively high visible reflectances and therefore they are easily confused with snow. In this case, they are distinguished from snow by their low near infrared reflectance on visible ratio. For example, the clusters are assigned as cloud shadows if the NDVI values for the doubtful clusters are less than 48, whereas if NDVI is greater than 48, the clusters are classified as partial snow for the image of 16 January 1991.

It should be stressed that the NDVI threshold for detection of low cloud/cloud shadows varies with different images. It must be examined and assessed with care for different images. For example, the NDVI threshold for the analysis of 13 February 1991 image was assessed as 50. That is, the uncertain clusters with NDVI values less than 50 was assessed as low cloud/cloud shadow while those equal or greater than 50 were assessed as marginal snow.

3.4 Cirrus detection by T11μm - T12μm

Cirrus clouds are characterised by higher T11μm - T12μm brightness temperatures differences than cloud free surfaces. The assumptions are that the T11μm - T12μm difference depends on the atmosphere only (Saunders and Kriebel 1988). However, land emissivity and the variation between nighttime and daytime conditions should be considered and caution should be exercised in using the algorithm. For example, a temperature inversion which is frequent over land at night-time will decrease the T11μm - T12μm difference, whereas a surface overlaid by colder air (which is the case for the oceans or lands during the day) presents the reverse effect. Also, the threshold setting for cirrus detection must be dealt with caution as snow areas may be misclassified as cirrus.

An example of using T11μm - T12μm difference for cirrus detection is for the analysis of AVHRR image of 16 January 1991. After the snow classification, three general classes were identified initially, i.e., snow, clouds and others. However, some misclassification errors could be observed by visual inspection of the AVHRR image and the classified results. Pixels over the ocean have been classified as snow which were likely caused by the confusion between low clouds and snow, or the confusion between cirrus cloud and snow. Firstly, a threshold of 'AVHRR 4 - AVHRR 5 $<$ 1°C' was used to detect cirrus. By subtracting AVHRR band 5 from AVHRR band 4 using image "**ALGEBRA**" function in the ERDAS, a new image file was generated with the difference values between AVHRR band 4 and band 5. This file was then masked out for snow area only. If the pixel value for the masked file was less than 1°C, it was assigned as snow, otherwise it was assumed as cirrus. However, after recoding the image file with snow, clouds, cirrus and others, it was found that many known snow areas over land have been included as cirrus. Therefore, further examination was required to modify the algorithm and set a new threshold for cirrus detection. After a series of trial and error experiments, 'AVHRR 4 - AVHRR 5 $<$ 1.4°C' was seen to give the best result for discrimination of cirrus and snow. That is, T11μm - T12μm greater than or equal to 1.4°C was used as the threshold to detect cirrus while T11μm - T12μm less than 1.4°C for assignment of snow class. Similar experiments were applied to the discrimination of low cloud/cloud shadow and marginal snow for the AVHRR image of 16 January 1991 using different NDVI thresholds. For this image, good results have been achieved when using NDVI greater than 47 to threshold cloud shadow effects. Complete and partial snow were further separated using NDVI greater or equal to 50. Figure 3.1 shows a diagram with typical procedures for snow area classification and mapping. Plate 3.1 and Plate 3.2 present the result for the image of 16 January 1991.

3.5 Snow area mapping

Snow area mapping can be accomplished by going through the procedures described in previous subsections, i.e., data processing, classification, shadow detection, cirrus detection and snowpack description upon request. Therefore, a series of maps showing snow area over the UK have been obtained for study of changes in snow area extent and for further study on snow depth (e.g. Plate 3.3-a, -b, -c, Plate 3.4 and Plate 3.5).

3.6 Comparison between AVHRR and TM image snow classification

The TM image of 15 January 1991 covering Northumbria is cloud free and snow is seen on the ground (Plate 3.6). Statistical Clustering (STATCL), which is another method of unsupervised training within the ERDAS system, was used to perform the unsupervised clustering for the TM images. This method takes into account the homogeneity of neighbouring groups of pixels, instead of considering individual pixels equally. It is based upon the assumption that contiguous, homogeneous pixels usually indicate a spatial pattern

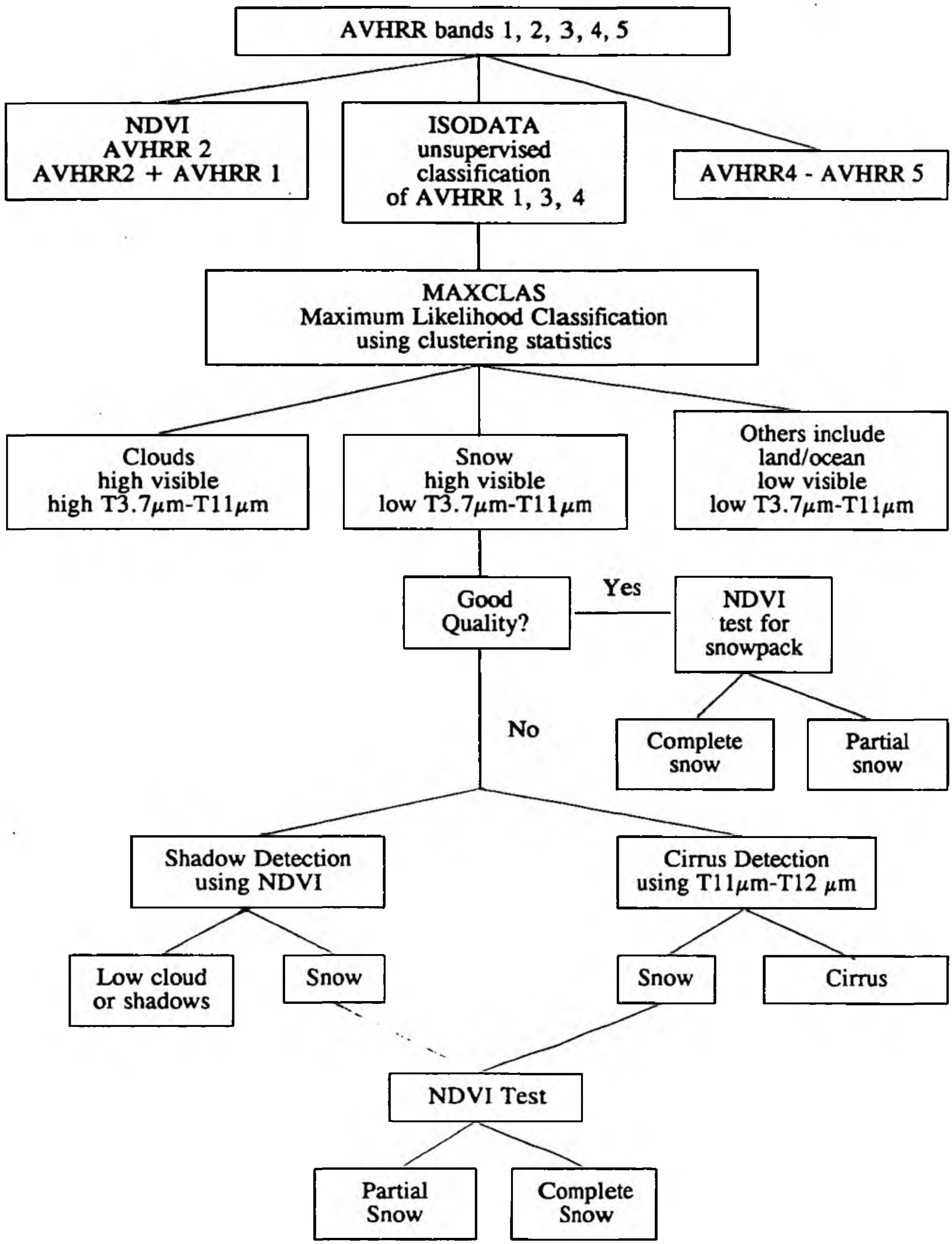
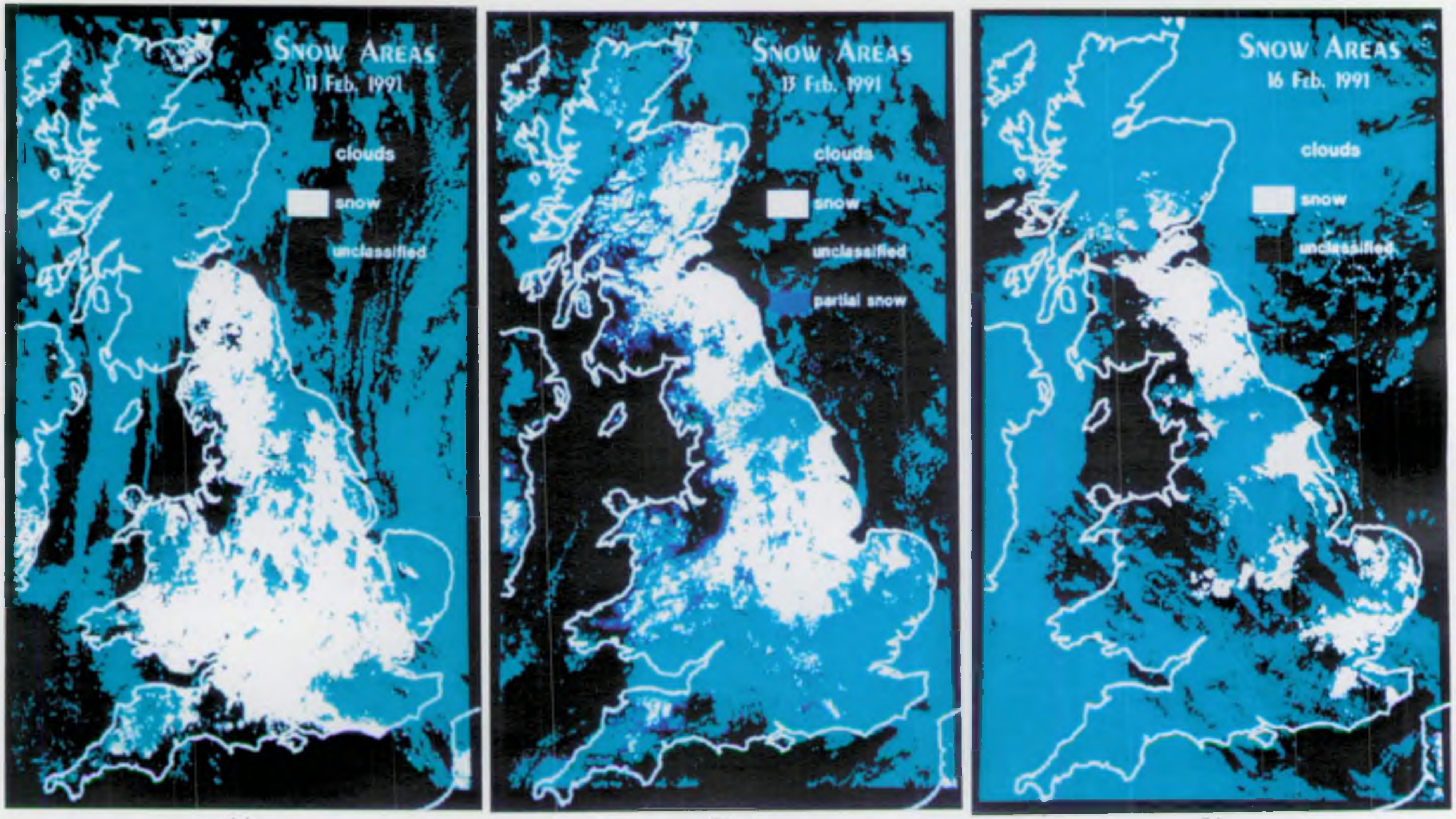


Figure 3.1 Flow diagram showing procedures for snow area classification and mapping.

Plate 3.1 Colour composite of calibrated NOAA-11 AVHRR band-1 (blue), band-3 (green) and band-4 (red) of the UK, 16 January 1992.

Plate 3.2 Snow area mapping for 16 January 1991 following the procedures in Figure 3.1 with identification of shadows, cirrus and partial snow and complete snow.



(a) (b) (b)

Plate 3.3 Examples of snow area estimates from the unsupervised classification of the calibrated NOAA-11 AVHRR bands 1, 3 and 4: (a) Classification result for 11 February 1991; (b) result for 13 February 1991 and (c) results for 16 February 1991.

Plate 3.4 Colour composite of calibrated NOAA-11 AVHRR band-1 (blue), band-3 (green) and band-4 (red) of the UK, 15 January 1991.

Plate 3.5 Snow area estimates for 15 January 1991 from the unsupervised classification of the calibrated AVHRR bands 1, 3 and 4 as shown in Plate 3.4.

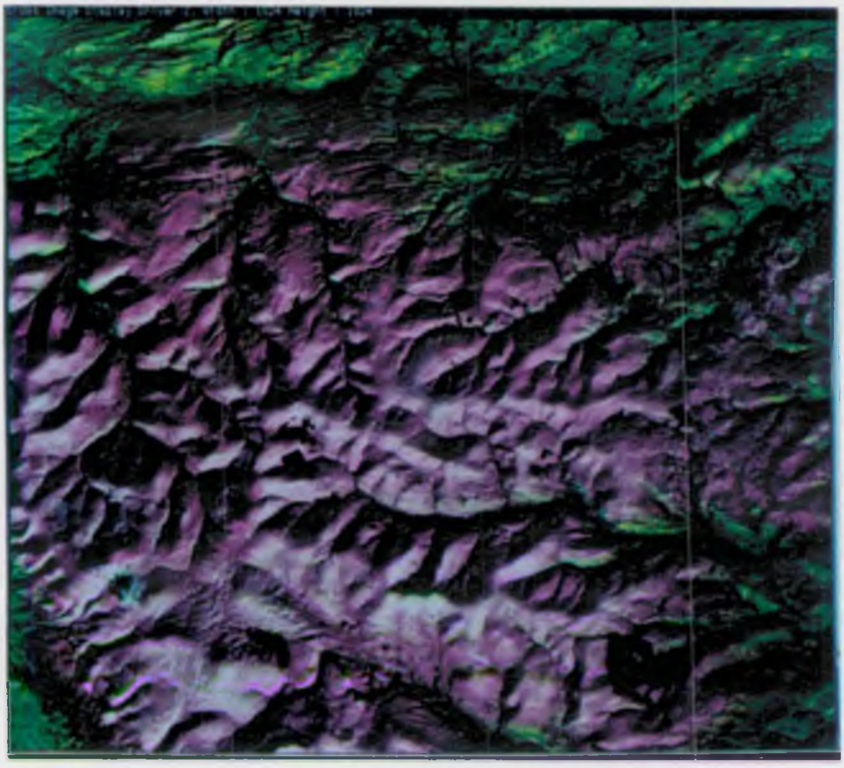


Plate 3.6 Colour composite of geometrically corrected TM bands 3 (blue), 4 (red) and 5 (green) of the Northumberland area (Landsat 5, 204/22, 15 January 1991). The high reflectance of snow in visible band-3 and near-infrared band-4, together with its great absorption in mid-infrared band-5 give the false colour of purple.

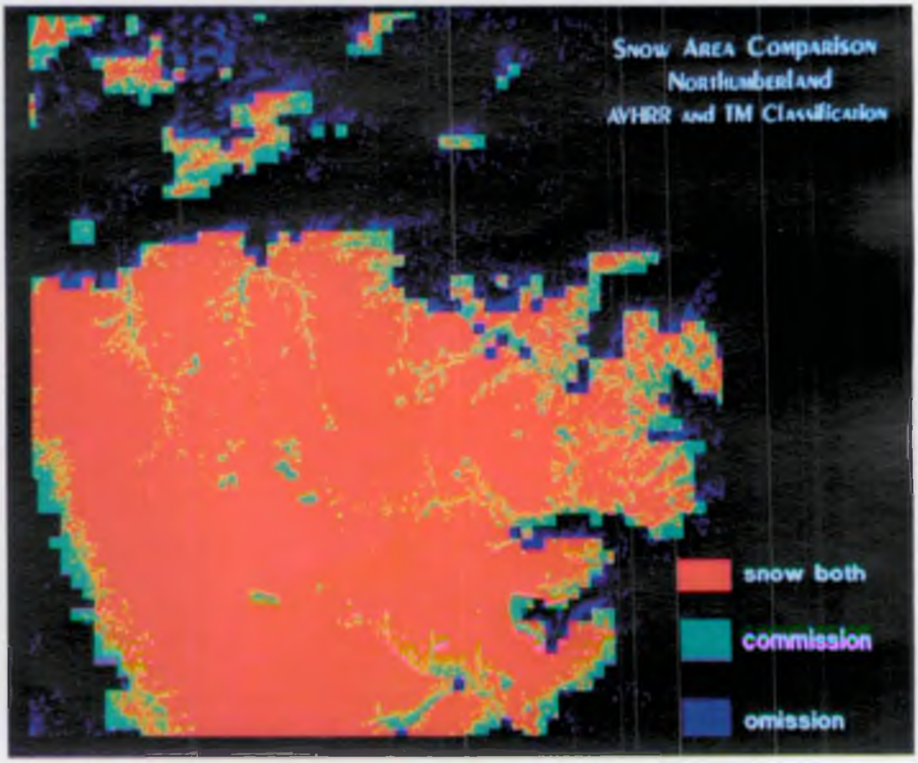


Plate 3.7 Snow area comparison between TM and AVHRR image classifications for Northumbria, 15 January 1991. Areas which have been classified as snow in both images are shown in red. Those classified as snow by AVHRR but not by TM are in green, indicating overestimates by the AVHRR classification. Blue shows areas identified as snow by TM but not by AVHRR.

within the data that is worth classifying. A 3 x 3 window was used for homogeneity testing in this study. Considering the fine resolution of TM imagery, the homogeneity of neighbouring pixels is important. The statistically clustered data was then classified using Maximum Likelihood Classification. The classification of TM bands 3, 4 and 5 gives good results of snow identification. Also, the image was registered to British National Grid in order to keep a consistent coordinate system to study images from different sources with different spatial resolutions or at different dates, or studying remotely sensed data in conjunction with existing maps. This was mainly achieved by analysing the chosen Ground Control Points (GCPs). The Root Mean Square (RMS) distance error, which is the distance between input location of a GCP and the transformed location for the same GCP, was kept to less than one pixel. Therefore, results of snow classification of AVHRR and TM images can be compared to assess the classification performance of AVHRR images. Both images were acquired for 15 January 1991 and comparison was limited to the area of Northumbria by British National Grid:

	Eastings	Northings
Top Left	360 000	580 000
Bottom Right	420 000	520 000

The comparison was carried out on a pixel by pixel basis after the pixel sizes of both classified images were interpolated and resampled to 50m x 50m. This offers an effective method of examining inclusive and exclusive classification errors. Plate 3.7 shows the spatial distribution of the snow areas classified by both image analysis and the overestimation and underestimation of AVHRR image mapping. The statistics are presented in the contingency table (Table 3.1). The overall agreement between two classifications can then be expressed by the total of diagonal elements of the contingency table as a proportion of the total entries for the whole table. A good agreement of 87.8% has been achieved between the AVHRR image and TM image analysis for 15 January 1991. 93% of the snow areas on the TM image has been identified on the AVHRR image classification.

By examining the spatial locations and spectral signatures of over- and under-estimation by AVHRR imagery analysis, similar trends were identified as reported by Bailey et al (1991) for the study in South Wales. The under-estimation of AVHRR image classification occurred mainly at the margins of snow fields because here the 1 km x 1 km spatial resolution of the AVHRR image does not classify as snow those pixels that are mixed snow and no-snow, but fall far below the classification threshold in terms of the fractions of snow present in the 1 km x 1 km pixel. Whilst for areas designated as over-estimation, in general, they lie within the snow fields and often because of topographic factors, are bare areas of a surface area significantly less than 1 km x 1 km.

In summary, the results of the comparison of a detailed TM image with an AVHRR image on 15 January 1991 suggest the adequacy of the level of refinements of the BRISCA algorithm and relation procedures of imagery analysis to merit their operational implementation as a whole.

4. SNOW DEPTH ASSESSMENT

4.1 General considerations

For adequate operational monitoring of snow depth, collateral data are needed to assist AVHRR image analysis. Current research is focussed upon snow depth algorithm development using GIS and image analysis. Snow cover variations reflect "parent" atmospheric processes and conditions operating at the time of snowfall. Terrestrial conditions also influence the pattern of snow cover distribution by modifying the dynamics of snow deposition. By incorporating ancillary data into a satellite snow depth monitoring algorithms, account can be taken of factors which influence patterns of accumulation during and after the event, as a result of energy and moisture transfer variations.

To establish the relationship between snow depth, satellite image features, and other factors which may affect this relationship, a preliminary categorisation of snow depth was initially undertaken for the UK data sets, by thresholding the visible band. AVHRR Channel 1 at visible wavelengths is the critical band relevant to snow percentage cover and snow depth estimation although it is recognised that snow depth monitoring based on brightness and textural characteristics of visible and near infrared imagery is best for shallow dry snow packs of up to a limited depth (Rott 1987, Chang *et al.* 1987). The spectral signatures of these clusters which were assigned as snow were further examined. Three general categories of snow depth were initially constructed as a result of the thresholding interpretation of mean values of AVHRR band 1 for the snow clusters. The spectral statistics and the spatial characteristics of each category were then scrutinized using GIS with the incorporation of collateral data such as slope, aspect, vegetation and snow wetness. A preliminary assignment of snow depth values for each depth category was attempted, based on the interpolation of the fifteen station records of snow depth in the Northumbria NRA region for 27 February 1986. During Phase II further work has been undertaken using the acquired more images for the snow events during 1990/91 and the available ground survey data of snow depth. As a result, the relationships between snow depth and satellite signals at different wavelengths are now better understood and more snow depth classes have been defined together with the depth value assignments.

4.2 A preliminary three-category classification of snow depth

Based upon the snow areas identified from the unsupervised classification with adequate accuracy, the spectral signatures of those clusters which were initially assigned as snow were further examined for the AVHRR image of 27 February 1986 (Bailey *et al.* 1991). Three general categories of snow depth were created by thresholding the AVHRR visible band. To study that image, those snow clusters with a mean ratio of radiance for AVHRR band 1 above 100 were assessed as deep snow while clusters with the visible band mean below 80 were assigned as shallow snow. Any other snow clusters which had a visible band mean value between 80 and 100 were assessed as medium snow. The result shows that the spatial distribution of those snow depth categories accords well with the general terrain variations which often have a close relationship with snow area and snow depth.

An attempt was made to assign snow depth values to the three categories already established, based upon the interpolation of the available snow depth records from the 15 ground stations in Northumbria NRA region for 27 February 1986 (see Table 6.2 in Bailey *et al.* 1991). These point data were mapped and compared with the three-category classification of snow depths. As a result, the following group values were then assigned for the three category classification of snow depth (see Plate 6.1 in Bailey *et al.* 1991):

shallow snow:	< 5 cm
Medium snow:	5 - 15 cm
Deep snow:	> 15 cm

4.3 Defining more snow depth classes under different conditions

4.3.1 Acquisition of more snow depth data

In order to conduct a further study of snow depth, "ground truth" data was obtained for the snow events during 1990/91. Data were purchased from the Meteorological Office's national snow survey archive for February 1991. These were compiled and mapped to British National Grid projection. Some 600 stations contributed to the snow depth data set and these snow depth point data have been used to generate digital images for comparison with satellite signals and AVHRR image products. In addition, snow survey data for the winter of 1990-91 for Northumbria region have been provided by the regional NRA. There are nine fixed stations which record snow depth, density and water equivalent. In addition surveys were carried out by the NRA field staff during the period of heaviest snow from 8-14 February 1991. A summary of the information obtained has been provided for comparison with image analysis. The nine fixed stations and their locations are as follows:

Station Name	Location in NGR
Blindburn	NT 829 109
Bingfield Combe	NY 982 728
Chillingham Barns	NU 052 262
Harpington Hill	NZ 336 266
Lartington	NZ 012 179
Lockwood Beck	NZ 668 141
Ministeracres	NZ 025 556
Tindale	NY 623 596
Tinstall	NZ 063 407

Table 4.1 lists the general information on the available snow depth data for study of the snow events during 1990-91.

After receiving AVHRR images for the snow events during 1990/91 and obtaining more data of snow depth from ground survey reports (NRA and the UK Meteorological Office) as described above, further attempts have been made to establish the relationship between snow depth and AVHRR spectral reflectances. Most of the work described below is based upon the comparison between the image pixel values and the point data.

4.3.2 Examination of snow depth and satellite signals

The point data for snow depth were mapped into the British National Grid, compatible with the ERDAS image format. A GIS file with snow depth data for a selected date can be generated using the RSU acquired program **"plot_met_snowdata"** or **"plot_nra_snowdata"** adapted for different snow survey reports and formats. The required inputs for running the programs are: selection of a particular date; name of data file containing snow survey data; definition of information of interest, e.g. snow depth, density or snow water equivalent; and name of output ERDAS file. The ground survey data can then be displayed spatially on the ERDAS system once the process is completed.

In order to investigate raw relationships between snow depth and the AVHRR visible band,

Table 4.1 Available snow survey data for the winter 1990-91

Date	No. of records	Data characters	Files for data storage
Dec. 1990	14 records available Northumbria region	snow depth, density water equivalent	nrasn1290.dat
Jan. 1991	16 records available Northumbria region	snow depth, density snow water equivalent	nrasn191.dat
Feb. 1991	41 records available Northumbria region	snow depth, density snow water equivalent	nrasn291.dat
	600 stations over the UK	snow depth snow water equivalent purchased from the Met. Office's national snow survey archive	metsnd291.dat metsnw291.dat

scatter plots have been made using the available software "S" for the pair data of snow depth and AVHRR visible band Digital Number (DN) values. Using the data for 13 February 1991 as an example, snow depth data from the Meteorological Office's national snow survey archive plus those from the Northumbria NRA give a total of 303 non-zero points. As Figure 4.1 shows, there is a trend for higher AVHRR visible band values to correspond with greater snow depth, although this positive correlation is rather statistically weak (correlation coefficient: 0.47). In attempts to establish such a relationship, it is important to separate the cloud-covered and cloud-free areas, and the regression line should only be drawn on the basis of those points which have both snow depth records and have been classified as snow in the AVHRR classification. Figure 4.2 shows the scatter plot using the snow depth values and the visible reflectance for the pixel points which are not concealed by clouds. The correlation coefficient in this case is 0.69. Thus, improved correlation has been achieved using the "cloud free" pixels for establishment of relationship between snow depth and visible reflectance. Meanwhile, it is important to realise that for those points lying on shadowed aspects, visible band data may reveal relatively low reflectances while snow might be deeper in reality. This assumption was confirmed in later work. Clearly, a large scatter remains, much of which seems likely to be related to vegetation and other surface effects. Time permitting, attempts will be made to the disaggregation of such effects before the end of the present Contract.

A further, more reasonable way of intercomparing satellite (areal) and surface (point) observations of snow depth using real numerical values, the ground survey snow depth data were next grouped into several categories for convenient comparison with image classification outputs. The GIS file with snow depth data from the Meteorological Office's national snow survey archive and the NRA Northumbria data for 13 February 1991 was

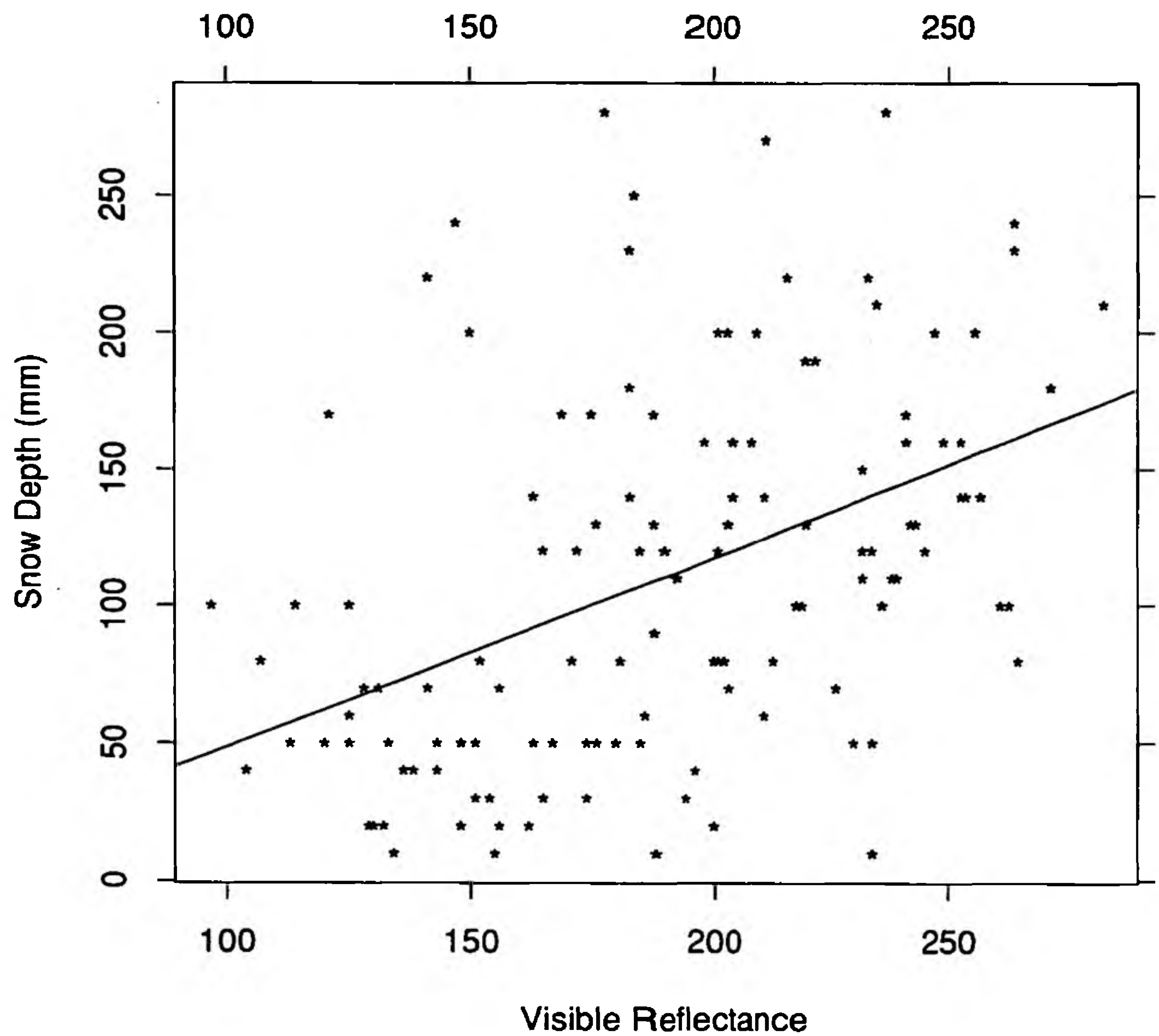


Figure 4.2 Scatter plot of observed snow depth values and the AVHRR visible band 1 reflectance, excluding these points concealed by clouds in the AVHRR image (UK, 13 February 1991).

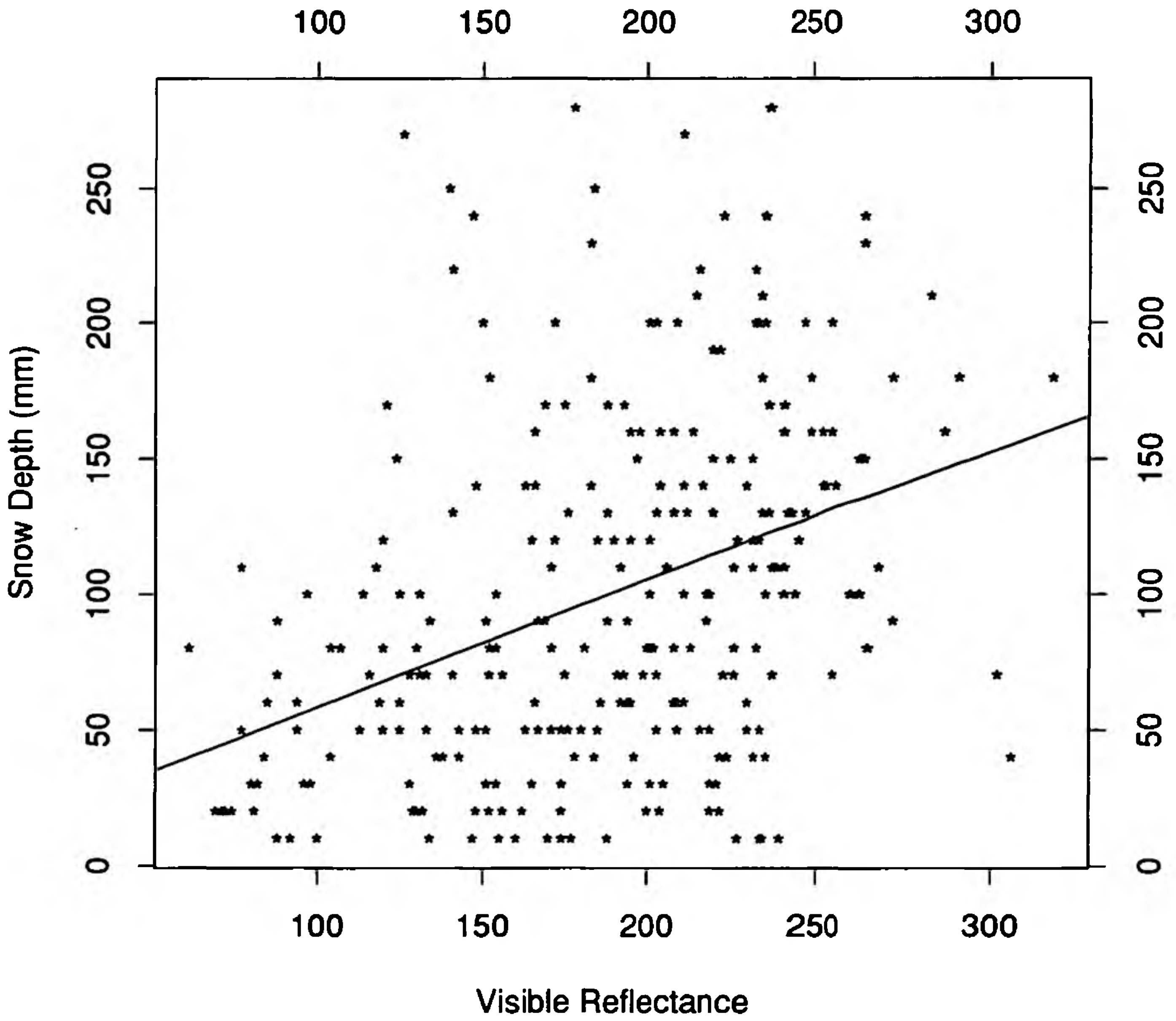


Figure 4.1 Scatter plot of snow depth values from ground survey reports and the albedo (multiplied by 10) at AVHRR visible band 1, using the total 303 non-zero pairs of point data for the whole UK on 13 February 1991.

Table 4.2 Number of points in snow depth groups from image categorisation and ground survey reports (13 February 1991).

	Snow depth groups from ground survey reports				
Image categories	Shallow (< 5cm)	Medium (5 - 15cm)	Deep (15 - 30cm)	Very deep (> 30cm)	Total
Shallow	16	12	3	2	33
Medium	17	18	15	1	51
Deep	4	30	30	6	70
Total	37	60	48	9	154

recoded to the following groups:

1	shallow	< 5 cm
2	medium	5 - 15 cm
3	deep	15 - 30 cm
4	very deep	> 30 cm

The mean value of AVHRR visible band 1 was then obtained for each snow depth group. As a result, 150 points have snow depth measurements from ground survey reports and have been classified as snow area in the AVHRR imagery analysis. Among these 150 points, 37 points were in the shallow snow group with a mean visible band reflectance of 159, 57 points in the medium snow depth group with a visible mean of 197, 47 points in deep snow group with visible mean as 220 and 9 points were in the very deep snow group with a visible mean value of 211. Again, this shows a clear trend for an increase in the AVHRR visible band pixel values as the snow depth increases.

As described in the report (Bailey *et al*, 1991), the preliminary categorisation of snow depth was performed by thresholding the visible band of each snow cluster. In general, these categories correspond well with the depth groups of snow survey data (<5cm; 5-15cm; >15cm). Similar categorisation has been applied to the AVHRR image of 13 February 1991. The contingency table below (Table 4.2) shows the agreement between the snow depth categories and the depth groups from ground survey reports. In general, the depth categories correspond well with the ground data grouping. As would be expected, categorization becomes progressively more difficult as deeper snow categories are attempted.

However, a further examination of these snow clusters shows a discrepancy on the depth value assignment, resulting mainly from the signatures of the thermal Infrared bands. For example, one cluster was initially assigned as medium snow by thresholding its mean value of AVHRR visible band 1. But the lower mean values in band 3 and band 4 may suggest the existence of deeper snow. The low values in the visible band 1 might be due to the shadow effects. One the other hand, another cluster has a higher mean value in visible band 1 and thus was assigned as deep snow. But the relatively higher mean values in band

Table 4.3 Number of points in snow depth categories after the re-assignment and ground survey reports (13 February 1991).

	Snow depth groups from ground survey reports				
Image categories	Shallow (< 5cm)	Medium (5 - 15cm)	Deep (15 - 30cm)	Very deep (> 30cm)	Total
Shallow	15	7	2	1	25
Medium	16	33	14	1	64
Deep	6	20	32	7	65
Total	37	60	48	9	154

3 and band 4 suggest the warmer temperature for the cluster. Thus the majority correspondence with ground survey group is medium snow.

Thus, although the categorisation of snow depth by thresholding the visible band in the spectral signatures shows generally a good agreement with ground survey data grouping, it is insufficient to rely on thresholding the visible band alone in the spectral signatures for snow depth categorisation. One example could be the mis-categorisation caused by the reduction in AVHRR band 1 due to shadow effects. Therefore, alternative methods have to be sought to achieve more reliable results. An appropriate approach is to take into account all three bands (i.e. bands 1, 3 and 4) signatures in order to carry out a practical categorisation on snow depth.

4.3.3 Re-categorisation of snow depths

To support the points made in the previous Section, clusters which had been identified as snow in the unsupervised classification were reassigned to different snow depth categories, taking account the three band signatures. The summary table (Table 4.3) shows an improved agreement between ground survey snow depth groups and snow depth categories after the re-assignment.

However, the re-assignment of snow clusters failed to give more than three depth categories. More work has to be done in order to find the best way to take into account the three bands information to represent as many depth categories as possible.

4.3.4 Defining more snow depth classes

The spectral signatures of AVHRR bands 1, 3 and 4 were further scrutinised by masking out the no-snow areas of the image 13 February 1991. The aim is to reclassify the pre-identified snow areas. Different classification algorithms have been applied for trial and error experiments, together with different band combinations.

One of the available methods in ERDAS system for evaluation on the training signatures is to use "ELLIPSE" to view ellipse diagrams and scatterplots of data file values for every pair of image bands. Normal histograms for every class are estimated with the mean and standard deviations stored in the signature file. The mean and the standard deviation of every signature are used to represent the histogram in each band of each potential class. These normal distributions for two bands are plotted in two dimensional spatial space to produce a series of ellipses. If the ellipses in the scatterplot show extensive overlap, the spectral characteristics of the pixels represented by the signatures cannot be distinguished in the two bands that are graphed. By analysing the ellipse graphs for all band pairs, the signatures and bands which will provide accurate classification results can be determined.

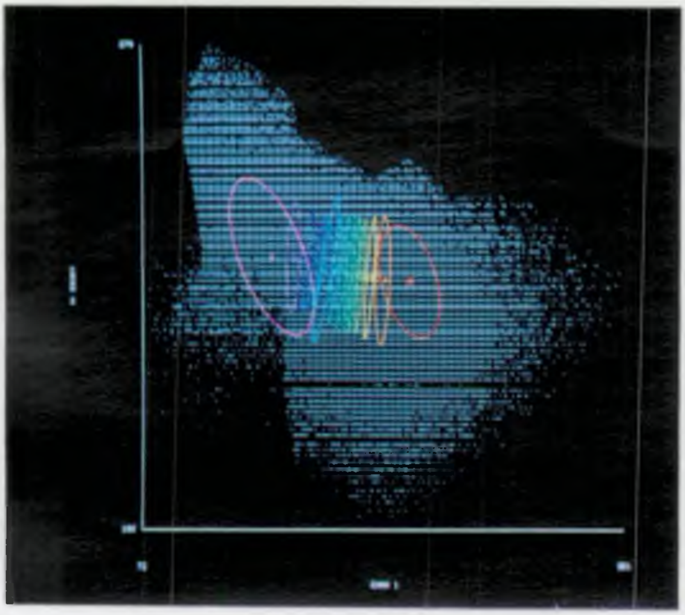
Plate 4.1 can be used to evaluate the signatures generated by ISODATA process for AVHRR image 13 February 1991, excluding the no-snow area. It shows the ellipses of the potential 15 snow depth classes in the scatterplot of every pair of AVHRR bands. It can be seen that ISODATA technique tends to discriminate clusters based on the variation on band 1. Overlapping of some clusters precludes a good classification. Therefore other methods have been sought. The compression of bands 3 and 4 and the incorporation of band 6 did not give better results because of the similar values of mean temperature in band 6 for different snow clusters. After a series of experiments, two spectral bands were used and considered sufficient to represent the major information. One is the calibrated AVHRR visible band 1 as used in the snow classification. The other is the first principal component of AVHRR band 3 and band 4, which gives information on certain ground features. The statistical clustering is found best to discriminate different cluster signatures (Plate 4.2-a,-b and -c). As shown in Plate 4.2-b, most spectral signatures can be represented by fifteen clusters without overlapping each other. This method has thus been used for the re-assignment of snow depth categories.

The summary table, together with the spectral signatures of the clustering, suggests a reasonable agreement as explained below. Plate 4.3 shows snow depth categorisation after the re-grouping. This follows the reasonable trend of increased/decreased snow depths. Therefore, this method forms the basis for further categorisation and quantification.

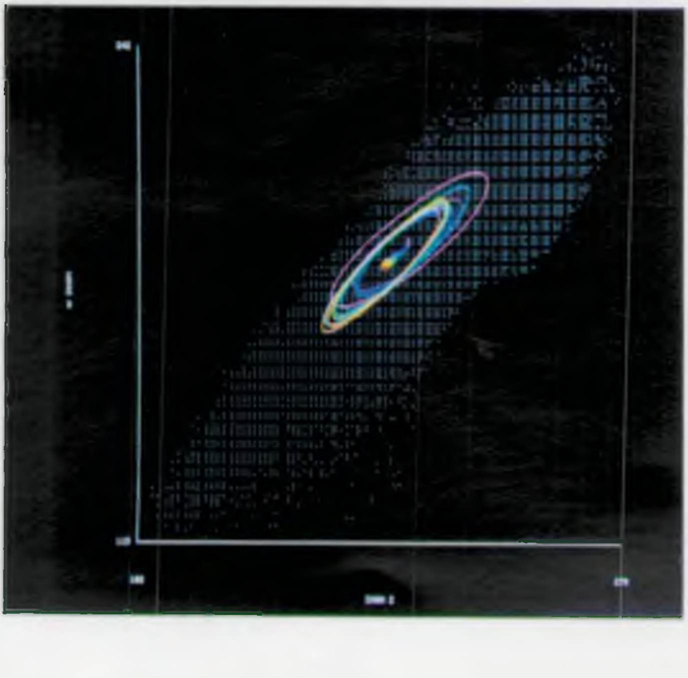
For 13 February 1991, snow survey data from the Meteorological Office plus survey data from the Northumbria region, give 303 point data of snow depth. Compared with the AVHRR snow classification, 154 point data of snow depth agree with snow/partial snow areas, 118 points were under cloud/shadows and 31 points fell over areas classified as others. From these statistics, it emerges that a good agreement can be obtained between AVHRR satellite classified snow area and ground survey data if these points which were not concealed by clouds were used as a sample set: 83 per cent of their clear sky values coincide in the case provided.

With respect to snow depth categorisation, the re-classification of snow areas permits improved categorisation of snow depth. Based on the statistical classification of AVHRR band 1 and the first principal component of AVHRR bands 3 and 4, 15 clusters were generated without final merge. Then, by analysing their ellipse graph and, by examining the summary table between each depth cluster and the snow depth group of the ground data, they were recoded into another five categories from shallow, shallow-medium, medium to deep and very deep snow. It is difficult to assign a range of depth values without overlapping. Therefore, the following assignments were made to show an expanded range of different snow depth categories and range of associated depth values:

Depth Category	Depth value range
1-shallow	< 5 cm
2-shallow-medium	5 - 10 cm
3-medium	10 - 20 cm



(a)



(c)

(b)

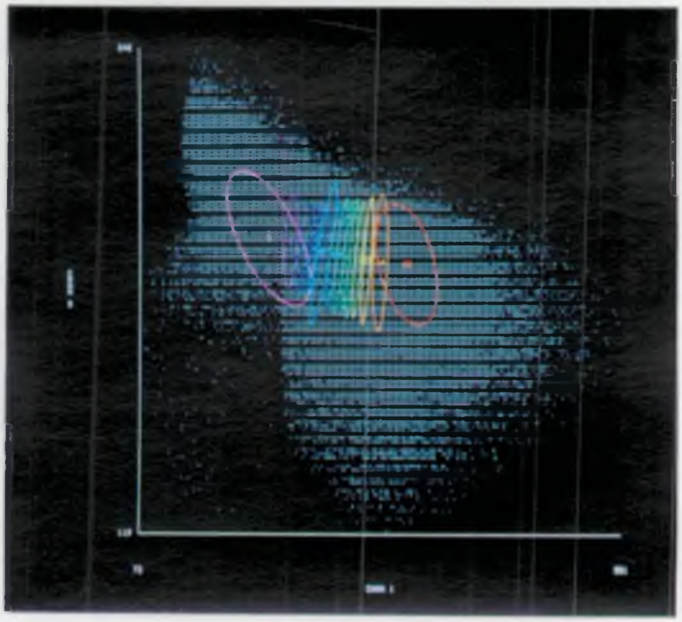
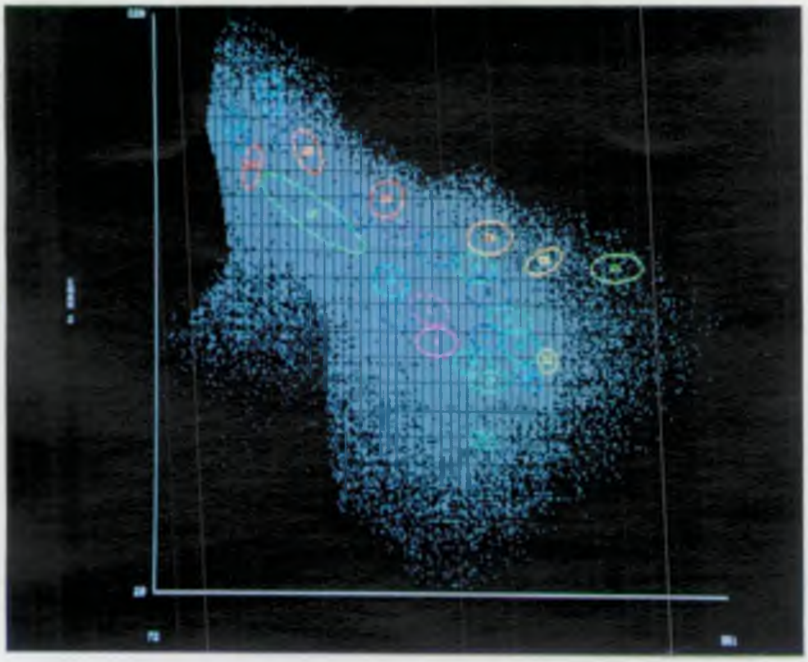
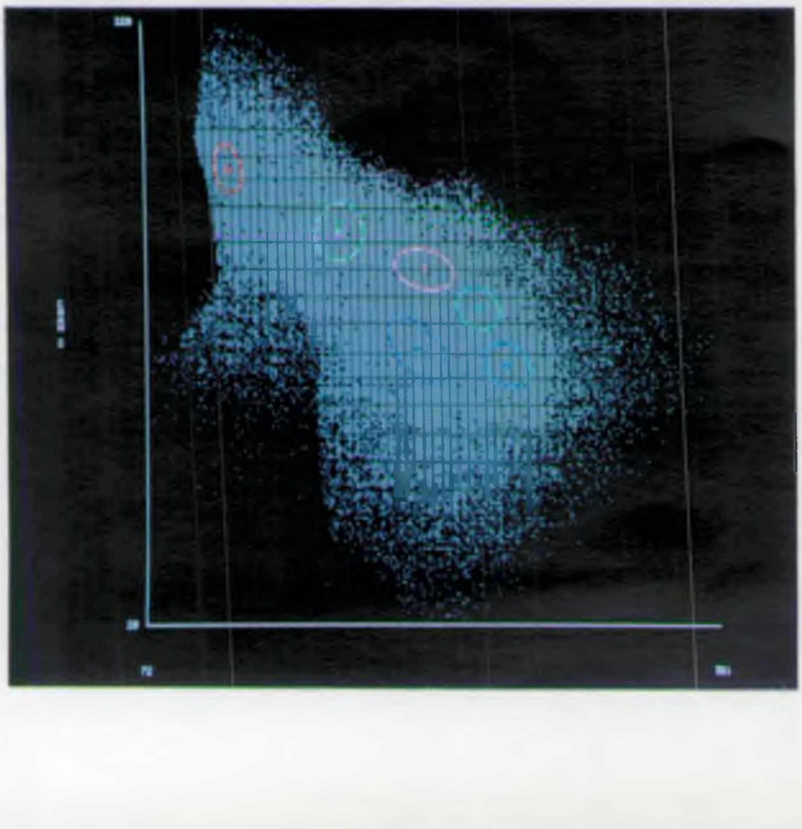


Plate 4.1 Ellipses of the potential 15 snow depth classes in the scatterplot of every pair of AVHRR bands excluding no-snow areas of the image, 13 February 1991: (a) AVHRR visible band-1 (horizontal) vs. infrared band-3 (vertical); (b) visible band-1 (horizontal) vs. thermal infrared band-4 (vertical); (c) infrared band-3 (horizontal) vs. thermal IR band-4 (vertical). It is clearly shown that two infrared bands are highly correlated due to similar pixel values of snow.

(a)



(c)



(b)

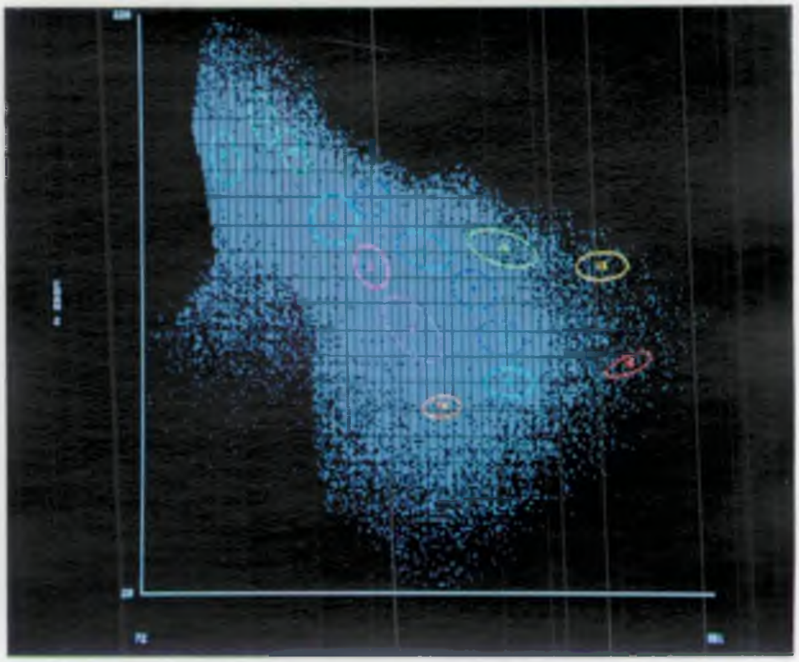


Plate 4.2 Ellipse diagrams and scatterplots of data file values for AVHRR visible band-1 and the first principal component of AVHRR bands-3 and -4, 13 February 1991 excluding no-snow areas. (a) 27 potential classes in the signature data; (b) 15 potential classes in the signature data; (c) 6 classes in the signature data.

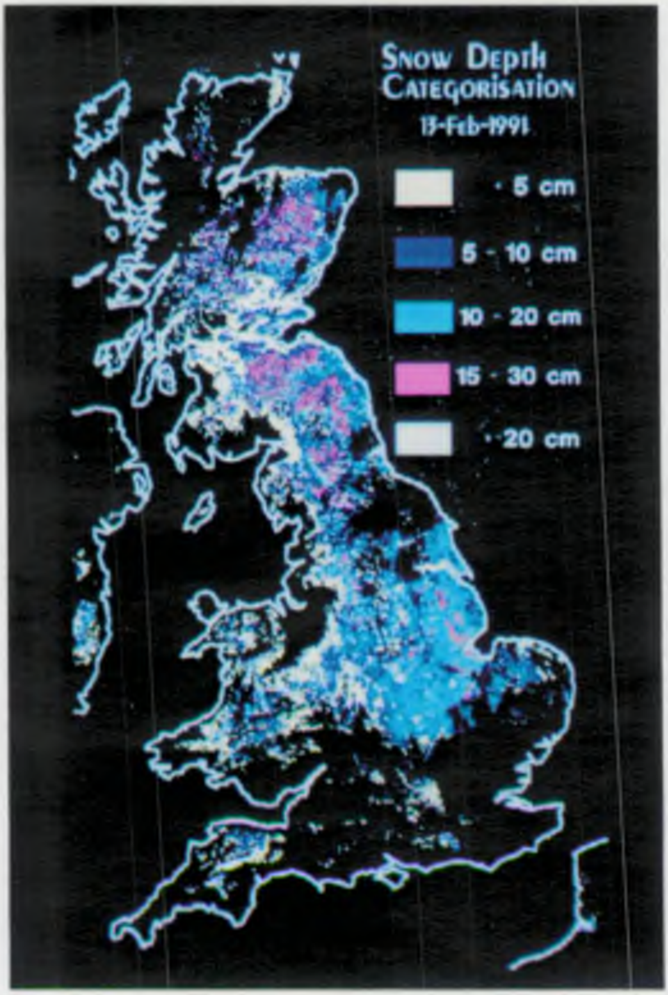


Plate 4.3 Snow depth categorisation by reclassification of AVHRR images, 13 February 1991, using band-1 and the first principal component of band-3 and 4 for snow areas only as established by snow area estimates (see Plate 3.3(b)).

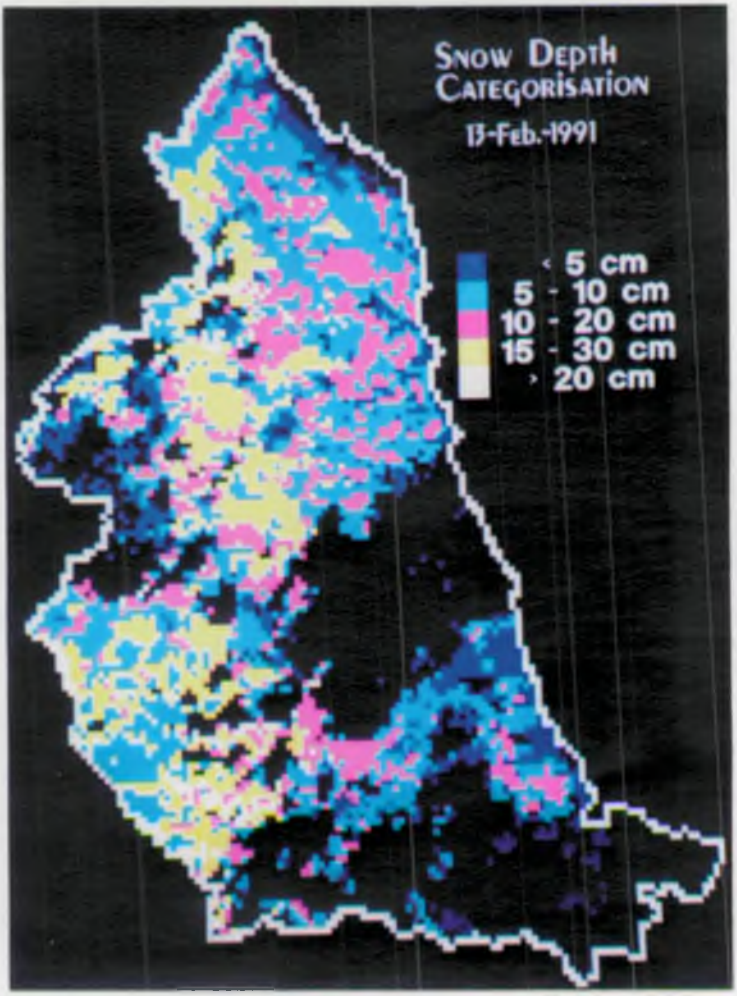


Plate 4.4 Snow depth categorisation for NRA Northumbria region, 13 February 1991 as in Plate 4.3.

4-deep	15 -30 cm
5-very deep	> 20 cm

A more detailed snow depth grouping has also been generated accordingly using ERDAS "**RECODE**" function for the snow depth data from snow survey reports:

Snow depth	Depth value range
Group 1	< 5 cm
Group 2	5 - 10 cm
Group 3	10 - 15 cm
Group 4	15 - 20 cm
Group 5	20 - 30 cm
Group 6	> 30 cm

Table 4.4 presents a summary showing good agreement between each depth category in image analysis and snow depth groups from ground surveys.

Table 4.4 Percentage agreement between snow depth groups from image classification and ground surveys, whole of UK, 13 February 1991.

Image categories / Snow survey	Shallow (<5cm)	Shallow-Medium (5-10cm)	Medium (10-20cm)	Deep (15-30cm)	Very deep (>20cm)
< 5cm	49.15	13.16	6.67	5.00	0.00
5-10cm	22.03	28.95	10.00	0.00	0.00
10-15cm	13.56	18.42	40.00	15.00	0.00
15-20cm	6.78	15.79	23.33	40.00	0.00
20-30cm	5.08	15.79	13.33	35.00	66.67
>30cm	3.39	7.89	6.67	5.00	33.33

4.4 Prospect for further assessment of snow depth

Having established the relationship between snow depth classes generated from the satellite imagery and ground data for snow depth at the national scale, the emphasis of the work moved to the regional level. The selected cases examined were for the NRA Northumbria region. Plate 4.4 shows the snow depth mapping for the NRA region on 13 February 1991 with the same categorisation scheme as in Plate 4.3. Further, the assignment of snow depth classes has been performed for the image of 15 January 1991 at both national and regional levels (Plate 4.5 and Plate 4.6).

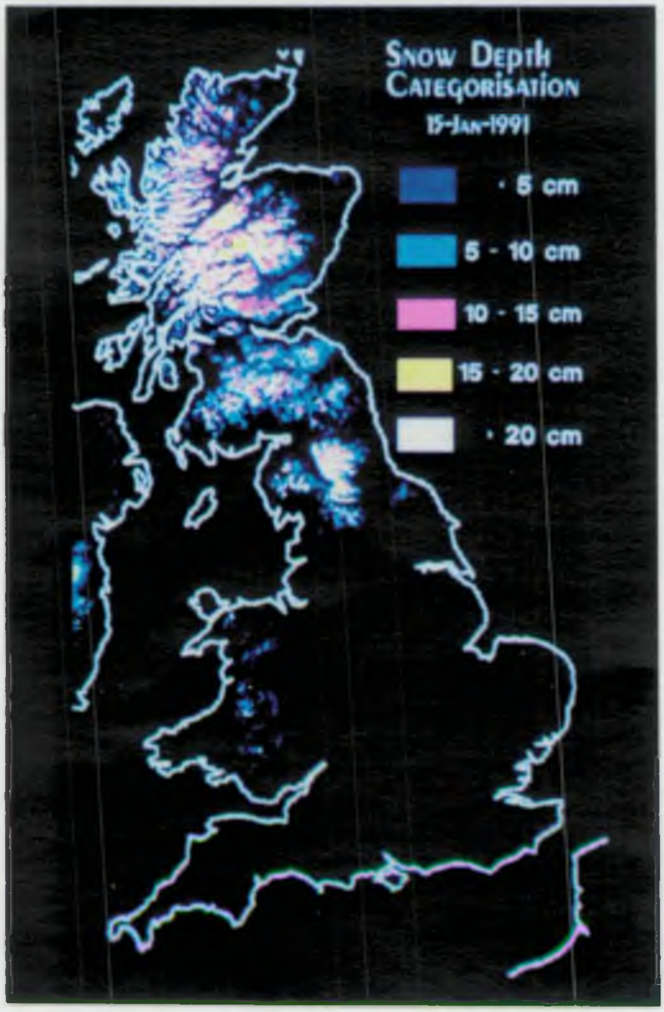


Plate 4.5 Snow depth categorisation of the UK, as in Plate 4.3, 15 January 1991.

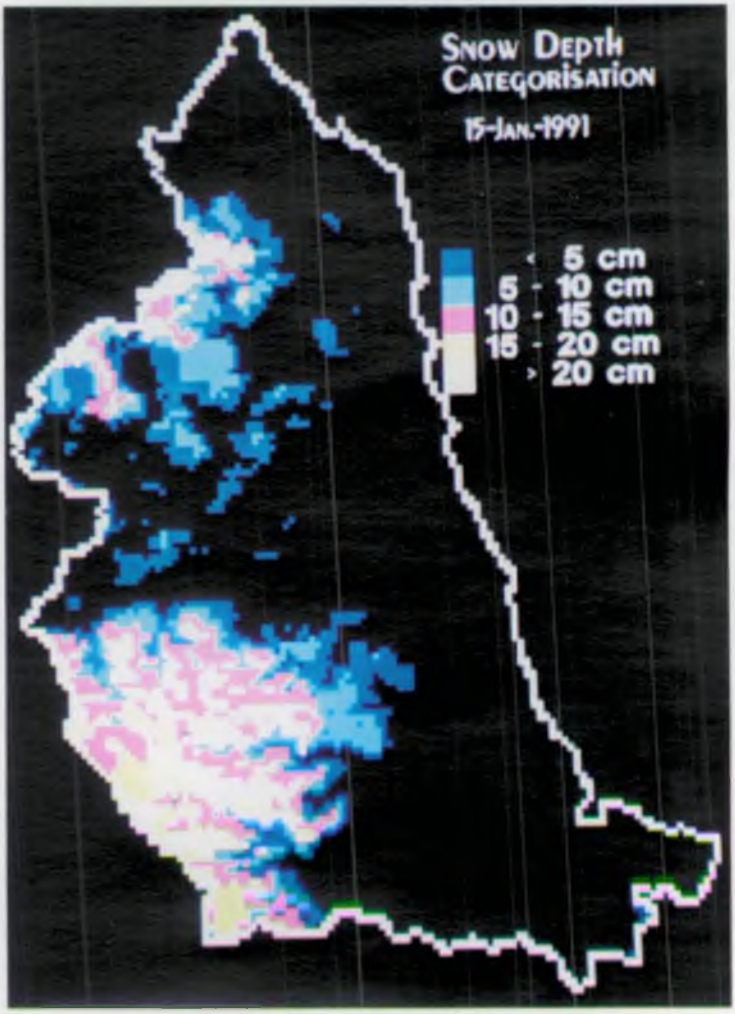


Plate 4.6 Snow depth categorisation for NRA, as in Plate 4.3, Northumbria, 15 January 1991.

5. USE OF GIS

For adequate operational monitoring of snow area/depth, collateral data is needed to assist high frequency pass AVHRR image analysis so that account can be taken of factors which influence patterns of accumulation during and after the snow event as a result of energy and moisture transfer variations. The relationships between snow cover variability and elevation, slope and aspect are being investigated using digital terrain models (DTM).

The rationale behind the implementation of a topography element in a GIS data base is that there are recognised relationships between snow cover and elevation, aspect and slope. Generally it is accepted that in mountainous regions, there is a location specific, linear relationship between snow accumulation and elevation (US Army Corps of Engineers 1956). However, elevation alone is insufficient to account for snow depth variations in a region because slope and aspect also influence deposition of snow. Terrain slope is related to topographic precipitation rain rate as demonstrated by Rhea and Grant (1974). Aspect controls on snow depth variations are important not only during the snowfall event, but also through their influences on the evolution of snow cover distribution after the event. This is done by their effects on energy and moisture transfer budgets. By quantitative examination of these three controls in relation to snow cover distribution, refinement of the satellite algorithm is possible.

5.1 Extrapolation of snow area beneath clouds

Cloud cover has been seen as the main constraint on the possible operational implementation of the satellite monitoring of snow over England and Wales based on AVHRR images. However, the possibility exists of integrating remote sensing analysis and a GIS data base for the extrapolation of snow area under clouds for selected areas of the UK. A previous study by Lucas and Harrison (1989) established that the area of snow concealed by cloud may be approximated by using snow-line altitude estimated and assuming a similar accumulation of snow above the calculated snow-line in these obscured regions as on observed surfaces. They defined the snow-line as the altitude above which at least 50 per cent of snow cover was observed. The magnitude of variation of the actual observed snow margin from the estimated snow-line was then employed to assess the altitude restrictions on snow distribution.

Extrapolations of snow area beneath clouds for two images have been attempted in this study. First, using outputs from a semi-supervised multi-spectral satellite snow monitoring method developed for the UK and a DTM for South Wales, estimates of snow cover in the partially cloud covered Northumbria of the same date (27 February 1986) were made (Bailey *et al.* 1991). Different factors of aspect and slope were taken into account in snow-line assessment. Statistics of the elevation data of South Wales were examined for the classified snow areas under different slope aspects. By examining the statistical distribution of the elevation data for each aspect, different snow-line altitudes were assigned for different aspects.

Once the snow-line altitude was decided for each aspect, areas of the Northumbria image concealed by clouds were examined separately for each aspect, in conjunction with the Northumbria DTM image. Areas above the defined snow-line altitude were then re-assigned as snow accumulated areas. The resultant images representing each aspect extrapolation were overlaid to show the snow extrapolation for the required Northumbria area. These extrapolated snow areas then replaced the clouds in the snow classification map (see Plate 7.1 in Bailey *et al.* 1991).

On the availability of more AVHRR images, and in order to get more practical

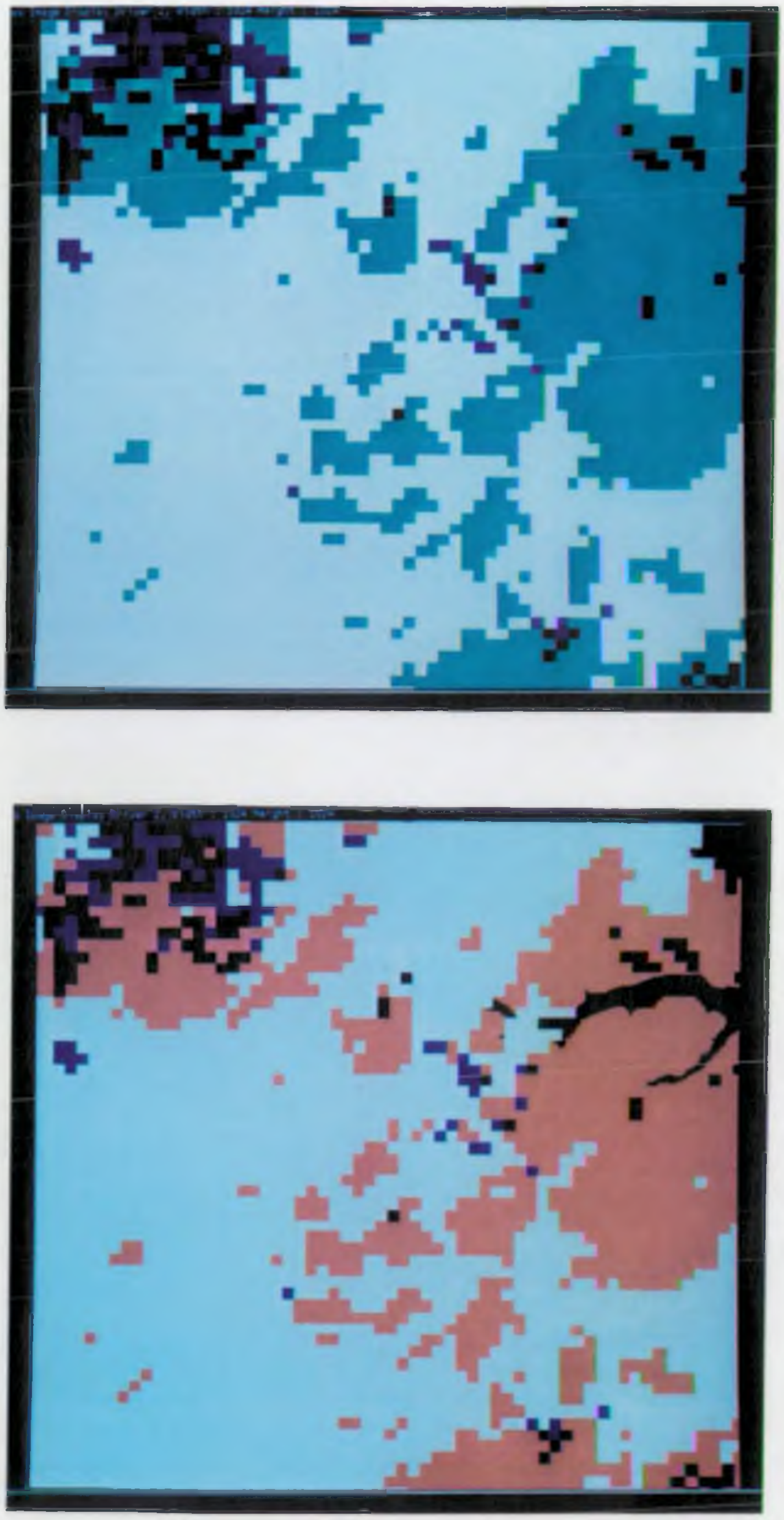
Table 5.1 Comparison between snow survey data and snow classification prior to the snow extrapolation beneath clouds (13 February 1991)

Image classification	Ground survey report			
	No Snow		Snow on the ground	
	Pixel No.	percentage	Pixel No.	Percentage
Unclassified	0	0	0	0
Complete snow	879080	61.46%	8380	87.11%
Partial snow	37450	2.62%	820	8.52%
Clouds	462760	32.35%	420	4.37%
Others	51090	3.57%	0	0
Total	1430380	100%	9620	100%

extrapolation of snow area under clouds, similar interpolation has been carried out using the snow classification results and the DTM information for the same Northumbrian region. The image used for extrapolation was the partially cloud covered Northumbrian scene for 13 February 1991. The elevation information of the classified snow areas for each aspect was examined on the basis of 30 metre elevation zones. The percentage of snow cover for each elevation zone in each aspect was then obtained by comparison between the number of pixels under snow cover with the total number of pixels within the altitude zone. The same snow-line altitude defined by Lucas and Harrison (1989) was used in the snow-line assessment, *i.e.* the altitude above which at least 50 per cent of snow cover was observed. As a result, the snow-line altitude of 50 m has been assessed for all aspects. Therefore, the cloud obscured areas have been re-assigned to extrapolated snow cover (above 50 m) and snow free areas. A full extent of snow distribution for the required area can then be constructed in conjunction with the snow classification map (Plate 5.1-a and -b).

In order to examine the performance of snow extrapolation beneath clouds, a comparison between snow survey data and classified image data has been carried out on a pixel by pixel basis before and after the snow extrapolation for 13 February 1991. Table 5.1 and Table 5.2 present the resultant agreements. It can be seen that all the 420 pixel points for which snow depth has been recorded but were initially concealed by clouds in the image have been correctly interpolated after the snow extrapolation process. Therefore, the accuracy and reliability of the method can be confirmed.

A preliminary examination has also been made of the methods that might be used to establish the relationship between slope angle and snow-line altitude. Slope exposure (exposure being the combined effect of aspect and slope angle) clearly influences snow distribution. However, the separation of the influences of the two elements of exposure presents some difficulties: slope angle may operate on snow distribution through its influence on solar radiation receipt per unit area, and its influence on wind flow patterns and hence snow deposition and gravitational forces may also be important; or it is possible that the functional relationship between slope angle and snow distribution may prove to be not only non-linear but also discontinuous, requiring modelling sophistication which is not yet attainable.



(a)

(b)

Plate 5.1 Extrapolation of snow areas beneath cloud using snow-line altitude assessment for different aspects for part of Northumberland, 13 February 1991: (a) prior to the extrapolation: in white - complete snow, blue - partial snow, aqua - clouds, black - others; (b) after the extrapolation: pink - extrapolated snow area beneath cloud.

Table 5.2 Comparison between snow survey data and snow classification after the snow extrapolation beneath clouds (13 February 1991)

Image classification			Ground survey report	
	No Snow		Snow on the ground	
	pixel No.	percentage	pixel No.	percentage
unclassified	0	0	0	0
complete snow	879080	61.46%	8380	87.11%
partial snow	37450	2.62%	820	8.52%
extrapolated snow	441508	30.87%	420	4.37%
others	72342	5.05%	0	0
Total	1430380	100%	9620	100%

5.2 Information extrapolation using successive images

Often, more than one AVHRR image is available for snow study on a given day and this increases the possibilities of obtaining more usable satellite images for snow mapping because clouds move. A sequence of satellite images, where different parts of each image are cloud free, can be classified and overlain to produce fuller areal information for the same snow day or for a snow event. The assumption is that snow condition for the two images remained the same and only the positions of clouds changed for the successive images. For example, Plate 5.2-a shows the snow area classification for AVHRR image acquired at about noon 10 February 1991 and Plate 5.2-b shows those around 2 pm on that same day. Assuming the snow conditions did not change significantly within the hours, the combined classified image reveals the fuller extent of snow distribution for that day as demonstrated in Plate 5.2-c. Also, the overall extent of snow areas for a complete snow event can be configured by using multi-date images. This topic will be treated in more detail in a subsequent Interim Report now being prepared. However, caution must be exercised as the areal extent of snow cover may vary significantly from day to day.

5.3 Incorporation of regional coverages for selected studies

NRA regional boundaries, and some catchment boundaries, have been digitised and stored as different GIS overlays. These have been carefully checked to ensure that they were registered to the BNG correctly. Therefore, imagery analysis for snow area and snow depth monitoring can be implemented at national or regional levels, or can be carried out for any selected catchment. Products for the Northumbria NRA region have been obtained, including snow area and snow depth classification for 15 January 1991, 16 January 1991 and 13 February 1991 (Plate 5.3-a, -b and -c).

5.4 Assessment of land cover effects

Assessment of the influence of terrain and vegetation has been taken on board. The intention is to address the effects of land cover on snow monitoring by reference to more detailed information on selected basins for which customised GIS data bases will be configured and used. Thus as described in Section 2.3, the forestry coverage for Northumbria has been digitised using "**GINGA**" software and transferred across the Ethernet to the SUN/SPARC network where the program "**draw_map**" can be used to produce a GIS overlay of forestry coverage for use with the ERDAS system. Plates 5.4-a and -b are examples of overlaying forestry coverage onto the colour composite of AVHRR band 1 (blue), 3(green) and 4(red) for Northumbria region for 16 January 1991 and 16 February 1991 respectively. It is easy to see that forestry affects the visible band reflectance for snow areas to a great extent. Most of the forestry areas would be identified as no-snow area by AVHRR classification. But it is likely that snow actually fell below the canopy of tree. As suggested by Lucas (1989), forestry areas totally enclosed by snow can be interpolated as snow areas. This offers an effective means to assess snow area under forestry. However, the usefulness of this method is often limited to the higher ground where snow exists more consistently. The fact is that many forestry areas are in the fringe between upland and lowland, and snow may appear in the upland area and disappear in the lowland. In this case, a weighting factor may be given for the interpolation of snow under vegetation. The application of this method is important for melting snow study.

Before the application of a weighting factor for the interpolation of snow under vegetation, some interesting points raised by Andersen of the Norwegian State Power Board during his visit to the RSU on 6 October 1992 may be noted.

According to Lucas (1989), "the ability to identify snow in forested areas was assessed by overlaying digital forest cover information onto the classified snow image and interactively delineating all wooded areas completely surrounded by snow cover. On the assumption of equivalent snow accumulation both within and outside these forest stands, the proportion of snow in forest identified by the classifier in the test region was calculated to be similar to the snow area detected in forests not completely contained within the snow field."

However, this assumption has been questioned and discussed by Andersen and others. Most importantly, snow accumulation within and outside forest stands could be very different because of interception, wind effect(s) etc. Interception of snow by trees can result in very little snow under forest. This is because, for the same amount of snow fall, tree leaves give a much greater areal contact between snow and the falling surface. Thus snow depth and snow accumulation could be significantly less than the surrounding area outside forest stands. This smaller amount of snow per unit area can be evaporated or blown away by wind relatively easily. Obviously, wind effects would be stronger for snow on trees than on the bare ground.

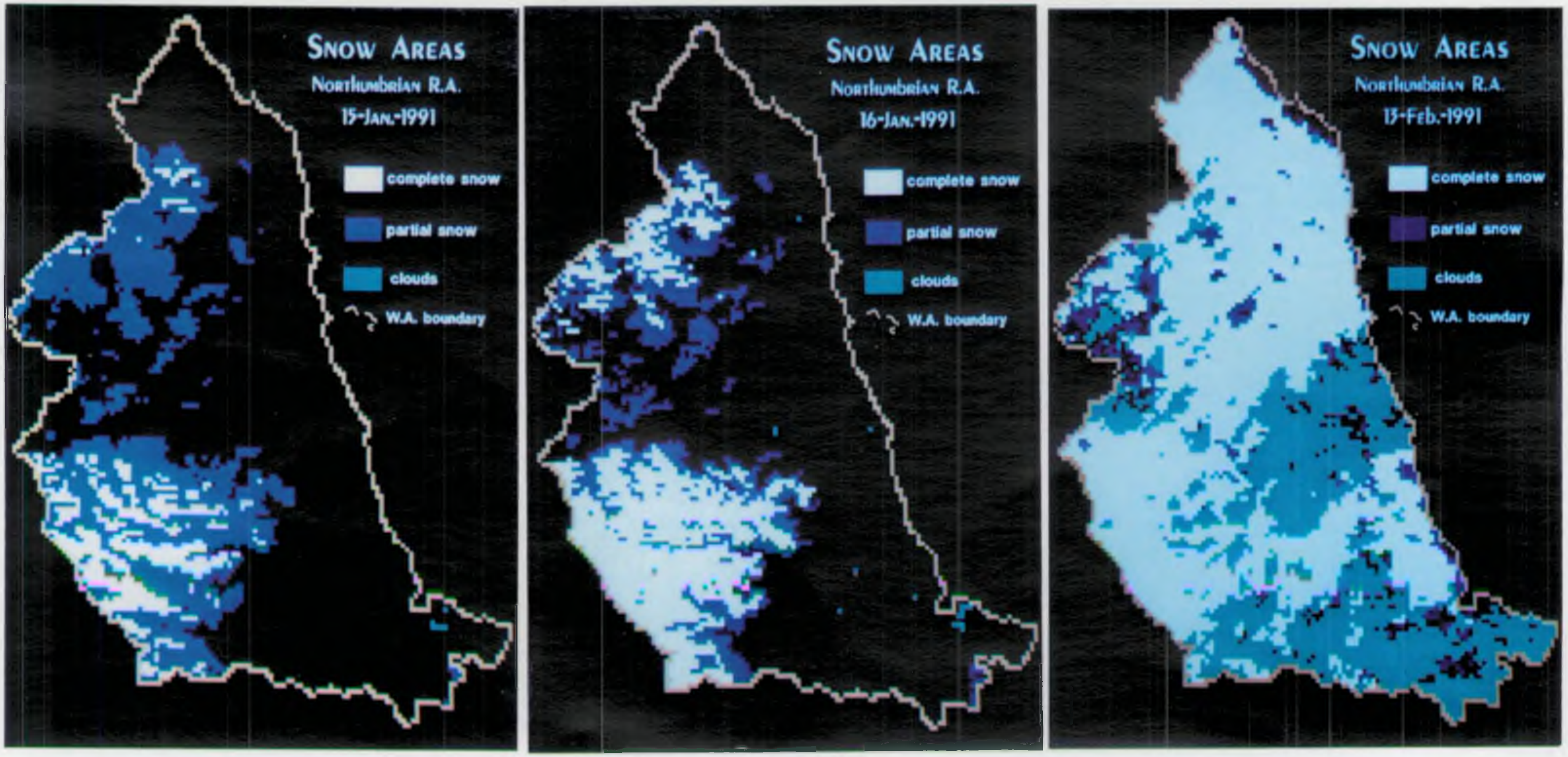
For such reasons, we have not thought it profitable to attempt further work on interpolation of snow area beneath forestry, for more detailed work needs to be done to assess the effects of vegetation on snow redistribution than the present Project Schedule allows.

5.5 Assessment of snow cover change

Another use of GIS is for assessment and analysis of changes in snow cover areas with respect to selected basins or areas as a basis for calculating inputs to flood forecasting models. This will be detailed in a separate Interim Report, now in preparation (q.v.).

(a) (b) (c)

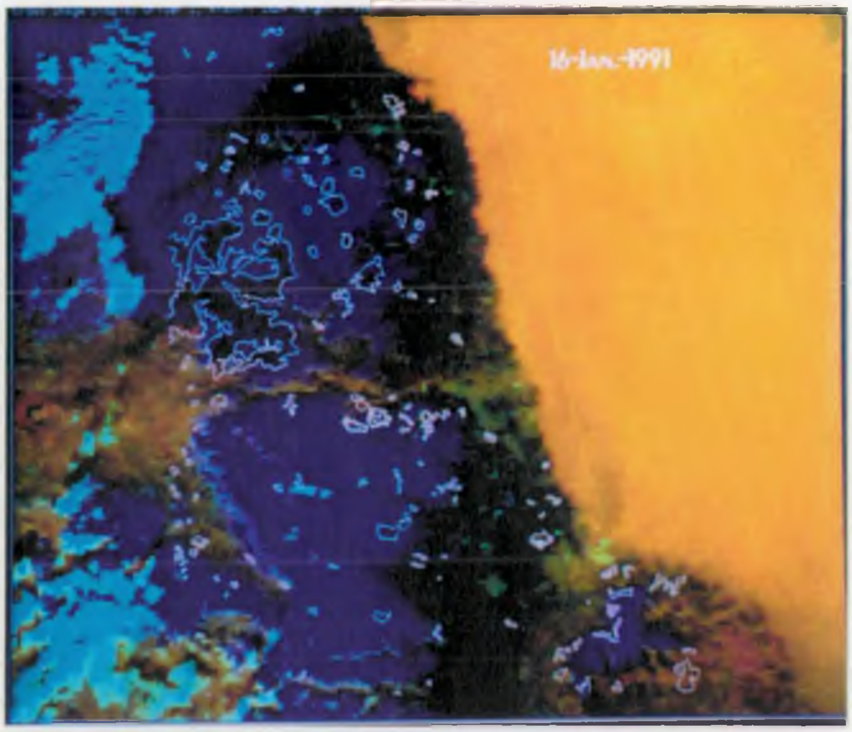
Plate 5.2 Snow area estimates for the whole of the UK, 10 February 1991: (a) noon image classification; (b) afternoon (c.2 pm) image classification; (c) mosaiked image of (a) and (b) revealing fuller extent of snow areas for the day.



(a) (b) (c)

Plate 5.3 Snow area estimates for NRA Northumbria region: (a) 15 January 1991; (b) 16 January 1991 and (c) 13 February 1991.

(a)



(b)

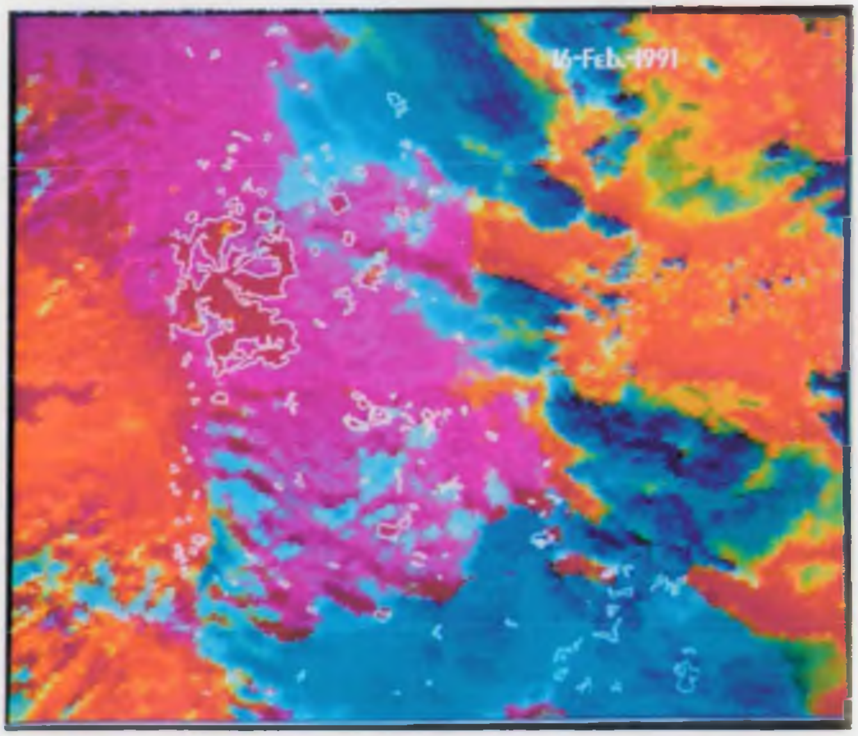


Plate 5.4 Example of overlaying forestry coverage on the colour composites of AVHRR band-1 (blue); band-3 (green) and band-4 (red) for Northumbria region. (a) 16 January 1991; (b) 16 February 1991.

5.6 Summary

Several ways of using GIS to assist imagery analysis and to extract more information have been demonstrated. Cloud cover imposes significant constraints on the use of AVHRR sensing of snow areas and characteristics. Greenhill *et al.* (1992) concluded 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 Northumbria 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. Relationships between satellite signals and factors regarding different land cover and terrain conditions can be examined with incorporation of GIS. The potential operational value of snow cover assessment by AVHRR imagery, which depends on the relationship between cloud occurrence and availability of satellite imagery during periods when snow is present, has thus been significantly increased.

6. CONCLUSIONS

In view of the progress made in Phase II as reported above, it has been demonstrated that satellite remote sensing facilities improved areal determinations of snow area and snow depth. The accurate registration of the satellite data to the British National Grid system enables easier handling of the data and will facilitate future operational approach scenarios which are being prepared.

We believe that the preliminary categorisation of AVHRR imagery for snow depth assessment, plus the incorporation of other ancillary data will provide a useful basis for continuous monitoring of snow depth. The development of a GIS data base and its integration with remote sensing analysis will be further advanced in relation to snow depth and water equivalent algorithms, the latter using data inputs from new passive microwave satellite sensing systems, a topic being addressed elsewhere in this Project. Still further improvements are envisaged when split window (6-channel) AVHRR comes about in the mid-1990s, especially in respect of wet verses dry snow discrimination.

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