Snow Cover Mapping with NOAA-AVHRR Images in the Scope of an Environmental GIS Project for the Russian Altai (South Siberia)

Erik Höppner[*)] & Nikolas Prechtel[**)]
***) Intermap Technologies GmbH, Weßling (Germany),**
****) Institute for Cartography of Dresden University of Technology**

Abstract

An efficient provision of actual, consistent, and reliable geo-information for modelling and map production is a prerequisite of up-to-date environmental protection and ecological planning. This should be accepted not only for the western world, where primary topographic and thematic sources are mostly more transparent and by far easier accessible. For about six years, a co-operative Russian-German project is on the way to collect geo-data, to set-up an integrative GIS-base, and to derive high-quality maps for the Central Altai Mountains in Siberia, an area with a high environmental status, reflected by Russian national authorities as well as by UNESCO's application as World Nature Heritage Area. The principal actors in the project are the Geographic Faculty of Altai-State University, Barnaul, and the Institute for Cartography of Dresden University of Technology.

In the present paper, the general GIS strategy and the actual state of our efforts will be summarised. Then, imbedded in the project scope, the work package 'Seasonal Snow Cover Mapping for the Russian Altai' (funded by a NATO collaborative linkage grant) will be discussed. The main information was taken from AVHRR satellite images, which have been classified for the years 1997 and 1998. Principles of data selection, and techniques for geometric and radiometric pre-processing will be explained, while the following striking points should be named explicitly: criteria to extract suitable AVHRR scenes (especially orbit, view angle on the target area, and cloudiness), rectification and geocoding of low-resolution imagery, classification using a hierarchical snow assignment scheme, extrapolation for no-data islands, transfer of results to GIS vector coverages, and map design.

The quality assessment is still preliminary. A more precise evaluation is currently planned for the inner study area - the Katoon-Ridge - using high-resolution satellite images and snow pattern analysis.

1. The Katoon National Park GIS as a frame for ecological data capture

1.1 General objectives

The principal objectives of the superordinate 'Altai Project' ***are environmental geo-data capture, GIS integration and thematic map production*** for a mountain area of 10,000 km^2. The main application fields for the GIS and the derived maps are seen in conservation, planning, and mountain research. The principal study area is encompassing contiguous protected zones in and around the Katoon-Range within the Central Altai (brief description e.g. by PRECHTEL 1998, more extensive e.g. by BUTWILOWSKI 1993). Moreover, a larger spatial context – the whole Russian Altai Mountains – is mirrored in our activities, wherever the spatial scale of data and the theme is demanding this. There are different responsibilities: the Russian Federation for the 'Katoon Zapowjednik' since 1991, the Altai Republic (a partly autonomous state within the Federation) for the 'Beloukha Nature Park', and the UNESCO for the World Nature Heritage Area since 1998 (part of the so-called 'Golden Mountains of the Altai'). This principal study area is only one focus of environmentalists, some 25% of the

Russian Altai Mountains have a protection status (KAISER & KÖNIG 1998). Their ecological value is well understood by the government and international organisations including NGOs, but contrasts with deficiencies in the de-facto management and the environmental awareness at the place. Several landscape zones are crossing the borders to Mongolia, Kasakhstan or China, and would profit from multi-national co-operative planning and steering. A dominant environmental intactness must, however, rather be attributed to a low pressure from a small indigenous population and few visitors than to an efficient environmental management. Unfortunately, it is nevertheless endangered: threads origin from historic events like fallout from the Semipalatinsk nuclear test plant, but also from recent ones: Wild camping and littering, frequent man-made forest fires, disturbance by trophy hunting parties and dodgy adventurers, etc.

Within the last six years, a collaborative long-term project of the Altai-State University, Barnaul, and the Institute of Cartography of Dresden University of Technology has been working on an informational base for environmental management. GIS and Remote Sensing is extensively used without neglecting traditional map products as a principal output. We believe, that a spin-off of such a project might also be some promotion of eco-tourism (PRECHTEL & BUCHROITHNER 2001). Because of an economically weak state of the area and little prospect for recovery of its traditional base (life stock, forestry and mining at some spots), an environmentally friendly tourism might be a potential loophole.

In the following, the general contents and some strategies of data organisation will be outlined to imbed the attempts of the snow mapping project as explained further down.

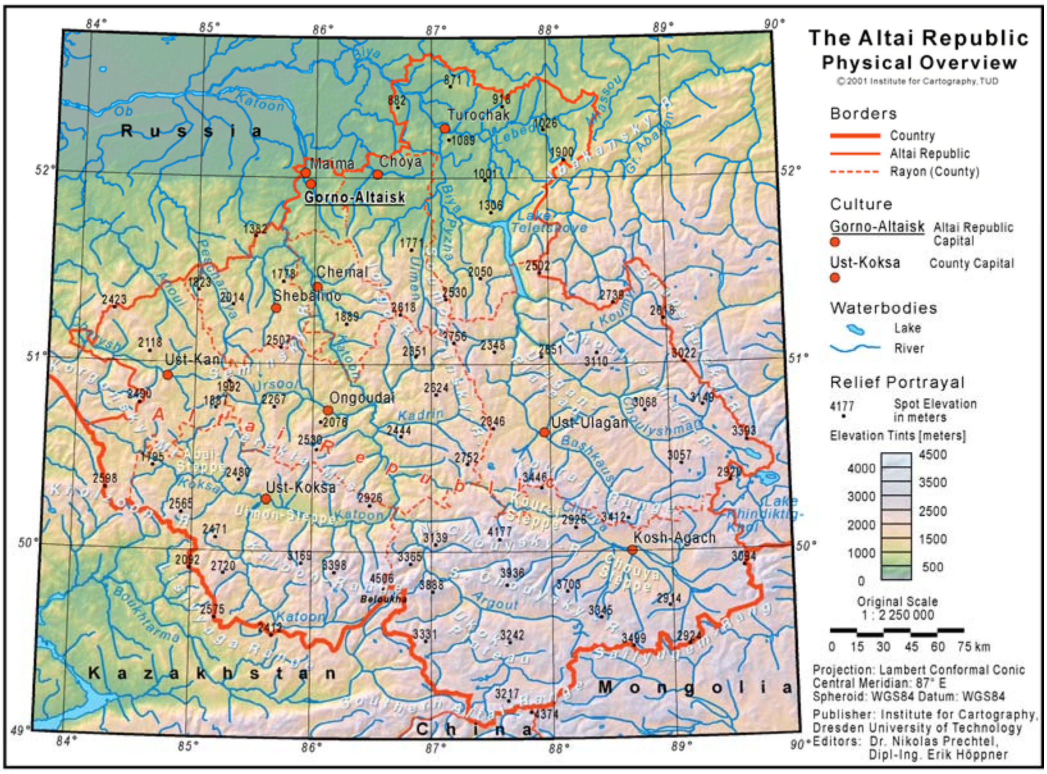


Figure 1: Map of the Altai Republic, the spatial reference of the snow cover study. Map presentation generated from GIS 'ALTAI 1000'.

1.2 Benefit of GIS integration

Even if reliable maps might be of greater help for the local conservationists at moment, a ***rigid GIS integration*** and secondary map production has proved to be the best solution. The GIS is much more than a digital map drawer. New data qualities are created through:

- forced geometric and semantic homogenisation of the source documents like topographic maps, satellite imagery, field survey documents as a first step towards data integration
- rigid integration using a comprehensive data model
- selection by semantic, geographic, and topological criteria
- modelling to be activated for detection of gaps, inconsistencies, and for new themes
- structured meta-data provision concerning data source, editor, temporal relations, processing history and other aspects.

In a completed initial phase, most work was centred around a topographic data base. In this context, some exemplary benefits of the GIS solution might be sketched:

A lot of problems of extracting relief info from topographic maps could be cured by numeric methods, like detection of missing contours and edge matching by co-ordinate transformations. Z-values could automatically be assigned to drainage arcs at contour intersections and intermediate sections be interpolated. Geometrical residuals between map-based and photogrammetric 3D points could be localised and freed from biased errors.

The drainage network, a major part of any topographic model, could be introduced in a consistent form as network model with node elevations (while a map typically uses combinations of 1D and 2D representations according to the width of a stream channel; PRECHTEL 2002). This, in turn, allowed not only to calculate drainage profiles, but also to trace back a whole drainage system or – in connection with the DEM – to derive catchment areas.

1.3 Two-level strategy

While working on the data base for the inner study area, accounting 10% of the Altai Republic's territory, it became clear, that some themes would require a wider spatial context. A decision for a multi-scale approach was made to account for:

- a maximum of detail in the protected zones of the Katoon-Range and their neighbourhood for ecological modelling (in respect of the primary data scales)
- modelling with and presenting of data of reduced positional and semantic accuracy and scale connecting to the ***whole Altai Mountains*** (e.g. meteorological, geological, administrative, population, transport data, etc.). A further target for the small-scale model was to convey basic knowledge on the Altai geography to 'non-experts', e.g. via internet.

This context area has been defined as the complete mountain system of the Russian and Mongolian Altai including its fringe with the southern parts of the West Siberian Plate to the north, the Kasakhian Ridge to the west, and the cold salt lake steppes to the east in Mongolia. The coverage is defined by a lat/long mesh with a south-western corner at 48° N, 82° E and a north-eastern corner at 53°N, 93°E. One typical application of the small-scale model is meteorological and climatic research including the wide-area snow distribution. A tabular data base has already been ingested to contain temperature and precipitation records from most of the Altai Republic meteo-stations. Also communication with low-resolution satellite meteorology can well be realised via this data base.

A brief overview on the technical parameters and the contents of the two GIS bases – termed *ALTAI 1000* and *ALTAI 100* - is presented in Table 1.

Altai-1000 (Overview Model), Lambert's Conformal Conical Projection, Cent. Meridian 87°E, WGS84 Spheroid, Coverage 48° N to 53°N and 82°E to 93°E			Altai 100 (Detail Model), Transverse Mercator Projection, Cent. Meridian 87° E, Krasovsky Spheroid, Coverage 49°40'N to 50°20' and 85°30' E to 87° E	
Category	**Info-Layer** *important attributes*	**Primary Source(s)**	**Info-Layer** *important attributes*	**Primary Source(s)**
[1] Relief	raster DEM 500m x 500m	reprojected and resampled from USGS GTOPO30	raster DEM 100m x 100m	TopoMaps 200,000 and MK4 (stereo) satellite images
			raster DEM 20m x 20m (P)	digital image correlation from CORONA stereo imagery
	lines and points *(elevation)*	contours calculated spot elevations from TopoMap 500,000	lines and points (*elevation)*	contours (rock & glacier), breaklines, spot elevations from TopoMaps 200,000
	raster (B&W): hill shading – raster (RGB): elevation tints	analytical generation	raster (B&W): hill shading – raster (RGB): elevation tints	analytical generation
[2] Drainage	lines: rivers polygons: lakes *(name, order)*	ONC Maps 1,000,000 TopoMap 500,000	lines: rivers polygons: lakes *(name, order, slope)*	TopoMaps 200,000; partial improved by delineation from images
			polygons *(catchment areas with ID)*	analytical generation
[3] Transportation	lines *(type of commun. link)*	ONC-maps 1:1,000,000	lines (*type of commun. link)*	TopoMaps 200,000; envisaged is a part improvement by GPS routing
[4] Settlements	points (*name, population)*	ONC Maps 1,000,000 TopoMap 500,000	polygons: settlement outline (*name)* lines: streets (P)	TopoMaps 200,000; internal street network from high-resolution images
[5] Forest Cover	polygons (unclassified)	TopoMap 500,000	polygons (unclassified)	TopoMaps 200,000
	polygons *(vegetation classes)*	reclassified from Global Land Cover Characterization	raster (*forest type)*	MK4- and IRS-1C LISSIII multispectral ortho-images and field observations
[6] Glaciers	polygons: glacier outlines (unclassified)	TopoMap 500,000	polygons, lines (*elevation, name)*	TopoMaps 200,000
			polygons (partly 3D) (*dates, surveyor, device)* (P)	high-resolution imagery between 1962 and 2001, GPS measurements
[7] Other Land Cover	polygons (*type)*	basically from various image data	polygons: natural land cover (*type)* (P)	from actual multispectral imagery
			polygons: man made land cover *type* (P)	from actual multispectral imagery and field observations
[8] Administration	polygons (*country, rayon)*	ONC maps 1,000,000 TopoMap 500,000	polygons (country, *rayon, protected zones)* (P)	TopoMaps 200,000 and other documents
[9] Meteorology	points: meteo-stations (attributed)	existing data sheets		
	raster and polygons: snow cover *(date)*	from AVHRR satellite data for the years 1997 and 1998		
[10] Morphology	polygons: maximum Pleistocene ice extent (unclassified) (P)	research documents of V. V. Butvilovsky	polygons (*facette attributes, morphological classes) (P)*	analytical from DEM, field survey and high-resolution imagery
[11] Important facilities	points (*national park facilities, scientific institutes, ...)* (P)	diverse documents and field survey	points *(national park facilities, services, ...)* (P)	diverse documents and field survey
[12] Terrestrial digital photographs			points: anchor points of camera position *(IDs)* (P)	from field campaigns

Table 1: Comparison of small (Altai1000) and medium-scale GIS (Altai100) Data Structure. Fields containing a (P) are currently under construction.

1.4 Relief models

In any ecological model of a high-mountain landscape, ***relief information has a central position***. Most natural processes are linked to primary (cell elevation) or secondary relief properties (slope, aspect, complex morphological unit). A start with the relief was – apart from subsequent modelling – also technically a must. All high-resolution satellite imagery had to be rectified with a precision, that would allow multi-sensoral image layer stacking. A rigorous geometric reconstruction of the data take configuration requires a DEM.

No regional DEM matching the minimum accuracy requirements was at hand at project start in 1995. One had to start with map digitising. The available 200,000 scale was pretty small, but the sheets had a very detailed relief portrayal. Their most severe shortcomings must be named: change of the contour interval between the sheets, partial edge mismatching, and 'no-data islands', where rock drawing excludes any quantitative information extraction. Gaps were photogrammetrically closed with MK-4 space photographs of nice quality. The measurement areas were blown-up to create data overlaps. Two point sets – map-based and image-based - could thus be compared. Discrepancies (from imperfect exterior image orientation, map generalisation, etc.) were detected. A systematic contribution to the residuals could mostly be eliminated. An estimated standard altitude error of the DEM lies around 35 m, but no concise reference allows a valid statistical evaluation.

Whereas a substantial effort was directed to a new Digital Elevation Model for the *ALTAI 100* GIS, the huge coverage of *ALTAI 1000* could only be filled with relief information from the popular *GTOPO30* data, which is globally available for land areas. The data set has been prepared by the National Imagery and Mapping Agency and forms a backbone for small-scale models until an improved global data set might eventually be provided from interferometric radar data of the SRTM mission. As indicated by the name, the original grid spacing is 30 arc-seconds or about 900 m in meridional direction. The original DEM was reprojected to the Lambert Conical Projection (comp. Table 1) and resampled to square cells of 500 m x 500 m to fit to the other data. Due to multi-source input to the original DEM, a homogeneous quality cannot be assumed. The combination with the various vector layers of *ALTAI 1000*, however, *prov*ed a good correspondence, especially with the drainage network.

2. Remarks on the role of snow cover in an environmental GIS

It is undoubted that ***snow cover is an ecological key factor*** in a mid-latitude high-mountain ecosystem. All living organisms interact with severe winter-time conditions and its critical energy budget, which a snow cover can partly alleviate, partly aggravate. Some principal spheres of influence, certainly all linked, might be isolated:

1. Snow as a *retention compartment* in the hydrological cycle: strong influence on the seasonal surface water discharge, and ground and soil water balance, too.
2. Snow as an important *climatic factor*: influence on the radiation budget and the sensible and latent heat flux. Ecologically also very important is the insulation effect of a snow cover to the soil underneath.
3. *Snow and man*: this includes all ecological and economical aspects of winter tourism and snow hazards to individuals and man-made structures.
4. *Snow and wildlife*: Influence on all vegetative cycles of plants (available water, daylight exposure, temperature oscillations in the upper soil layers, mechanical stress by snow

creep, ...) and, closely tied to the plant's life, the activity range of herbivores and, indirectly, carnivores. Moreover, a snow pack directly affects or sometimes blocks migration within and between seasonal habitats.

There are several adaptations to snow, which are in an evolutionary context a choice between avoidance and confrontation (comp. HINDELANG 2001):

1. Migration, meaning an escape to milder climates, when snow and cold avoids an endurance at the summer habitat.
2. Hibernation, a reduction of metabolic activity during a rest phase at a location, which is more favourable for keeping down the energy consumption.
3. Resistance, requiring physiological and behavioural adaptations to the stress factors; various ways are known like a specialised stature and musculature to allow propagation in deep snow, a seasonal colour change to improve camouflage, an effective insulation by a thick fat tissue and a dens fur, biochemical measures to avoid a freezing of body tissues, etc.

Many empirical studies cover the effect of the varying snow on wildlife. Very few exemplary cases shall be touched upon. Unfortunately, we could so-far not refer to comparable studies in the Altai. But a main purpose is to show, that a determination of snow distribution and endurance, the first result of the present study, is important, but only one stone in a mosaic:

A review of the North American bird census did reveal, that some bird species do react on snow depth (e.g. American Robin). Winter abundance was showing a peak around the Great Lakes in a dry, and some 500 miles further south in a snow-rich winter (MALONE, CERRETANI & KELLING 2000). Other observed species did not adapt their overwintering zones.

R. STARDOM (1977) has studied cervidae like Woodland Caribou (*Rangifer tarandus*), Moose and Whitetail Deer in respect of winter ecology in a mountain area of Manitoba. The animals were sensitively reacting not only on snow depth (through steering forage on arboral lichens or ground lichens, respectively), but also on snow consistency. The author rates a snow depth of 65 cm critical for the caribou, while D. CICHOWSKI (1993) estimates, that a 50 cm snow pack made the observed animals move to denser forested habitats with less and softer snow in her British Columbia study area. Also surface snow crusts or an excess density of the snow pack made bands evade to more favourable places. Whitetail Deer (*Odocoileus virginianus dacotenis*) were reacting already on depths above 25 cm (STARDOM 1977). A comparative investigation on the Altai Caribou (population is not well known, but appears in e.g. the list of endangered animals of the Altai Republic, VARIOUS AUTHORS 1996), the Maral Deer (*Cervus elaphus*), or the Siberian Roe Deer (*Capreolus capreolus*) would be desirable. For to include further rare indigenous mammals, the altitude range from steppe with inhabitants like the Mongolian gazelle, *Procapra gutturosa*, to high grounds with the worlds largest mountain sheep (*Ovis ammon ammon*) or the Altai Ibex (*Capra sibirica*) must be reflected. For wild goat species of the alpine elevation belt (*Capra i ibex L.* in the Alps) it has been shown, that insolation (also via its influence on snow depletion) is an important factor to mediate the dispersion and range quality (STEFANOVIC ET AL. 1985). Among the hibernating animals of the Altai, the brown bear (*Ursus arctos L.*) is certainly a prominent representative. Studies in their habitat requirements for the case of small Austrian populations have resulted in a semi-quantitative model (ASTE 1993), which clearly highlights snow as a principal climatic factor. The benefits of informational links of such a model to digital geo-processing, especially to remote sensing, has been proved (e.g. BUCHROITHNER ET AL. 1997).

At last it should be added, that the cited Altai species are under hunting pressure. Every internet user can find several adverts for hunting expeditions with a quick query. It can be doubted, that a sound assessment of the actual effects of this human interference exists, what leads back to the already stressed need of a good informational data base.

What could be expected from the satellite-based snow cover mapping?

By using AVHRR archive data as the principal available global information source, we can derive a binary (snow – no snow), irregularly spaced time series for a defined area with a standardised method. The sampling rate is obviously limited by the archived data. Theoretical and practical limitations concern geometric resolution, terrain features, cloudiness and the irradiation during data take (comp. below). Predictable data gaps can partly be bridged by extrapolation. A primary result can and has been achieved, consisting of snow cover snapshots over a time span of 2 years. A further evaluation will first try to clarify the classification quality by a local comparison to few high-resolution images. Then, secondary processing will try to estimate typical snow cover duration values. This should hopefully reveal ***typical patterns resulting from the individual macro- and meso-climatic setting***. Statements on depth and composition of the snow pack or its water equivalent cannot be made from these classifications. Such enhanced specification (comp. for Northern America HARTMAN ET. AL. 1996) would require a strongly extended observational base and seems to be pretty far from operational within Central Asia.

Nonetheless, we believe, that the new data layer will already in the given form be beneficial to clarify the environmental conditions and to improve an understanding of the habitats. The dramatic hydrologic effect of the water retention in the snow pack can be exemplified by Figure 2. The changes in the seasonal water discharge are enforced by a steep temperature gradient in spring causing a rapid snow-melt. Moreover, the late springtime floods after snow-melt cause major geomorphic effects: this can clearly be documented for the Katoon floodplain within the Uimon Basin. A synthetic image has been produced by multi-temporal layer stacking (red for 1962, green for 1971, blue for 1995). Saturated bright bands indicate a low correspondence of the main stream channels, while a bright yellowish colour indicates little or no change (comp. Figure 3).

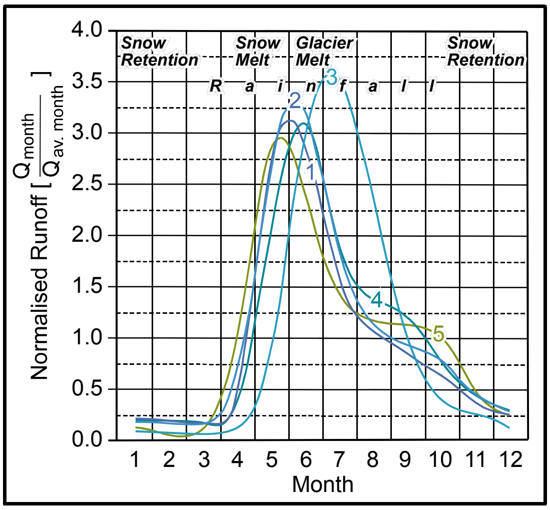


Figure 2: Runoff types of Central-Altai rivers: 1 - Katoon, 2 - Koksa, 3 - Koucherla, 4 - Terekta, 5 - Katanda. Except for No. 3 (glacier runoff dominating) all with strong snow-melt reaction.

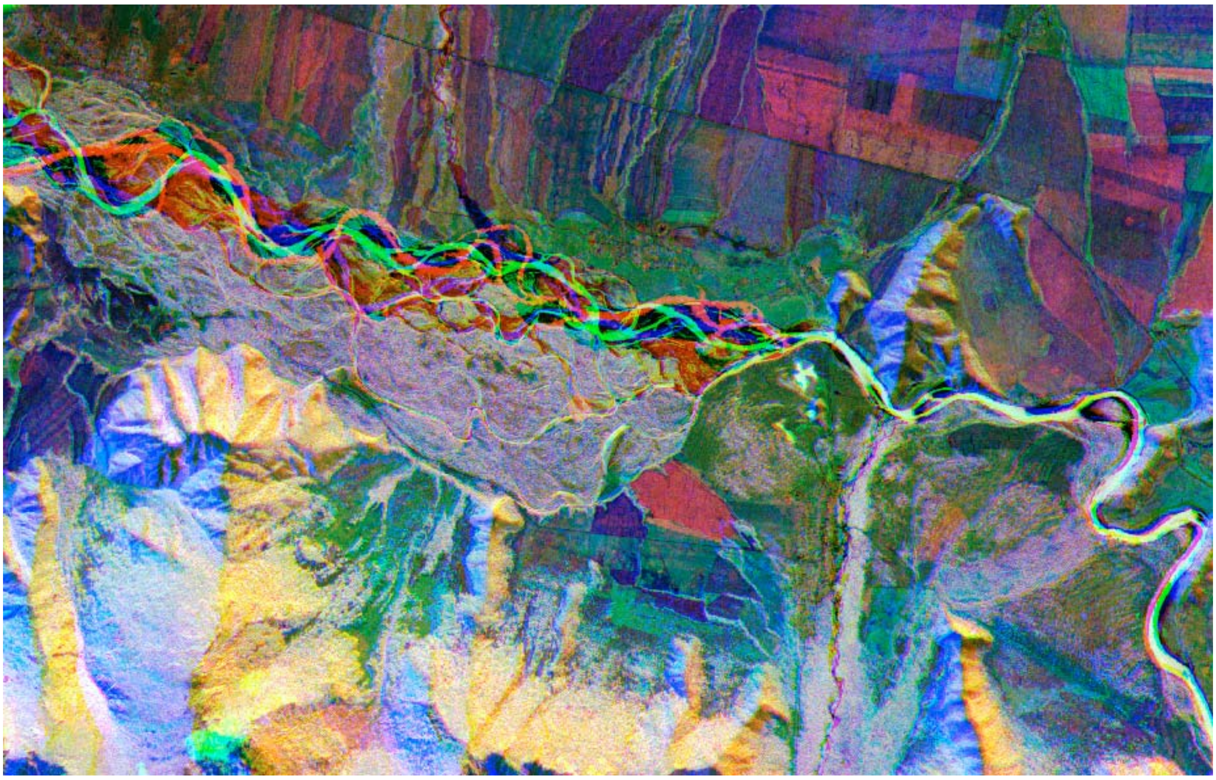


Figure 3: The effect of floods after snow-melt on the stream channel patterns in the Katoon floodplain near Moulta by a multi-temporal colour composite: situation '62 in red, '71 in green, '95 in blue.

3. Mapping the seasonal snow cover of the Altai Republic using AVHRR data

3.1 Satellite, sensor, data archiving and data calibration

The Advanced Very High Resolution Radiometer (AVHRR) is a multi-spectral scanner mounted on polar orbiting weather satellites of the US National Oceanic and Atmospheric Administration (NOAA). Orbiting our planet in a flight altitude of 800 - 850 km with an inclination of 98°-99° against the equator plane, one cycle takes 102 minutes. Due to the radiometers wide scan angle of ±55.4°, it is possible to completely map the earth within 24 hours***: global environmental observations with a high-frequency sampling interval*** become feasible. Each scan line is a radiometric record of a stripe measuring 2700 km in width. The nadir ground resolution of 1.1 km x 1.1 km degrades to 2.4 km x 6.5 km at maximum off-nadir angle, where a flat observation angle results in large panoramic distortions.

This study makes use of AVHRR data from the NOAA-14 satellite (Table 2).

Channel	Sensitivity [μm]
1	0.58 – 0.68 (visible spectrum)
2	0.725 – 1.10 (near infrared)
3	3.55 – 3.93 (middle infrared)
4	10.3 – 11.3 (thermal infrared)
5	11.5 – 12.5 (thermal infrared)

Table 2: Channels and sensitivity of the NOAA-14 sensor.

AVHRR data are permanently transmitted to the earth and, hence, data recording depends on the presence of ground stations in the receiving areas. In addition, data can to some degree be stored onboard and be transmitted to Central Command and Data Acquisition Stations (CDAs) of the NOAA National Environmental Satellite Data and Information Service (NESDIS) or related facilities at overpasses. After several quality checks, data get processed to Level 1b products and archived at the Satellite Active Archive (SAA) from where they can be downloaded free of charge by users worldwide.

Though already raw data (Digital Numbers or DNs) provide 'relative' information on type and state of a surface, sophisticated applications need a conversion of the DNs into physical measures such as reflectance or brightness temperature. This process of ***data calibration*** consists of pre-flight, in-flight and post-flight calibration (SOUZA ET AL., 1996; RAO & CHEN, 1996; CRACKNELL, 1997; NOAA POLAR ORBITING DATA USER GUIDE, 2002) and had to be applied directly after data selection (Figure 4). Figure 4 is also indicates the necessary preparational steps for the subsequent classification.

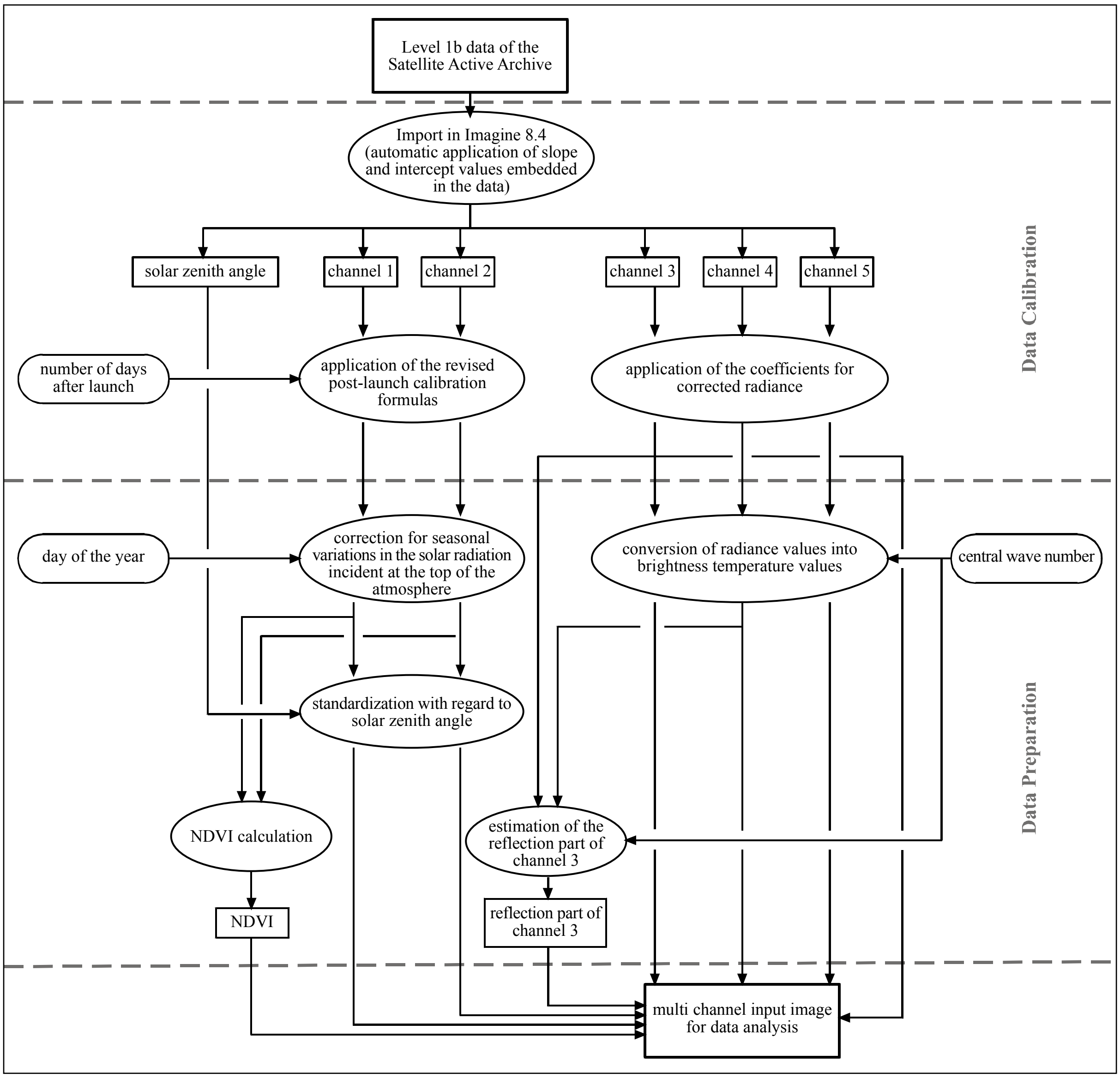


Figure 4: Data calibration and preparation steps.

3.2 Snow extraction from meteorological satellite imagery

While it is comparatively easy to separate snow-covered from snow-free land using spectral characteristics, it is challenging between snow and clouds. Many studies have addressed either snow or cloud extraction from AVHRR (SAUNDERS & KRIEBEL, 1988; GESELL, 1989; ALLEN ET AL., 1990; MAXSON, 1992; DERRIEN ET AL., 1993; SIMPSON ET AL., 1996 / 1998; VOIGT ET AL., 1999). These authors describe pixel-based, hierarchical methods using static spectral or bi-spectral thresholds, except for SIMPSON ET AL. (1996 and 1998), who is describing a cluster-based, hierarchical, dynamic, multi-spectral thresholding method.

Snow-covered and snow-free surfaces can be spectrally separated by different behaviour in the visible, near infrared and thermal infrared part of the spectrum. Snow-covered surfaces typically have a higher albedo in the visible (AVHRR channel 1), a lower albedo in the near-infrared (AVHRR channel 2), and lower temperatures than snow-free areas in a corresponding altitude. Problems can arise under poor illumination conditions at low sun elevations (SIMPSON ET AL., 1998), over densely forested areas where the crowns mask the snow (VOIGT ET AL.,1999), in the case of temperature inversions (ALLEN ET AL., 1990) or over sparsely vegetated, uniform surfaces with a high albedo (MAXSON, 1992).

The spectral signatures of snow and clouds depend on numerous environmental factors (HENDERSON-SELLERS, 1984; HALL & MARTINEC, 1985; ALLEN ET AL., 1990; YAMANOUCHI & KAWAGUCHI, 1992) and can be very similar. A discrimination is based on the minimum possible surface temperature of snow compared to clouds, a different reflective proportion of radiance in the middle infrared (AVHRR-3) and a different optical thickness of clouds as detectable with channels 4 and 5. The temperature criterion is unfit during isothermal atmospheric conditions, which can quite frequently be observed in mid and polar latitudes at wintertime.

The present study makes use of a pixel-based, hierarchical classification scheme consisting of six consecutive snow tests. It has been developed at Bern University (VOIGT ET AL., 1999). This threshold approach meets the requirements for snow mapping in a high-alpine terrain, reflects various related studies, is based on theoretical physical considerations as well as on empirical measurements, has been compared to other classification methods and been proved by in-situ measurements. Moreover, it is easily getting implemented and thoroughly documented. The threshold tests are ordered in such that the more specific the constrains of a step are, the later it is applied. Only pixels passing all tests are assigned to the snow class. This means that a ground cell shows predominant snow characteristics in its recorded spectral behaviour.

3.3 Data query, evaluation and selection

In spite of the existence of several open AVHRR archives, the ***SAA of NOAA*** is the only one known to the authors to provide data of the Russian Altai Republic throughout an extended time. The data query was a-priori restricted to NOAA-14 data of the years 1997 and 1998; almost 1000 images could be found in the SAA. Two additional criteria had then to be defined to evaluate their suitability:

- The study area had to be located around the image centre or at least in its vicinity with no parts falling outside of an 35° viewing cone (to limit resolution degradation and relief displacements).
- The cloud coverage had to be very low or – if not - to be distributed in a way that no major snow fields would be screened (for valuable classification results).

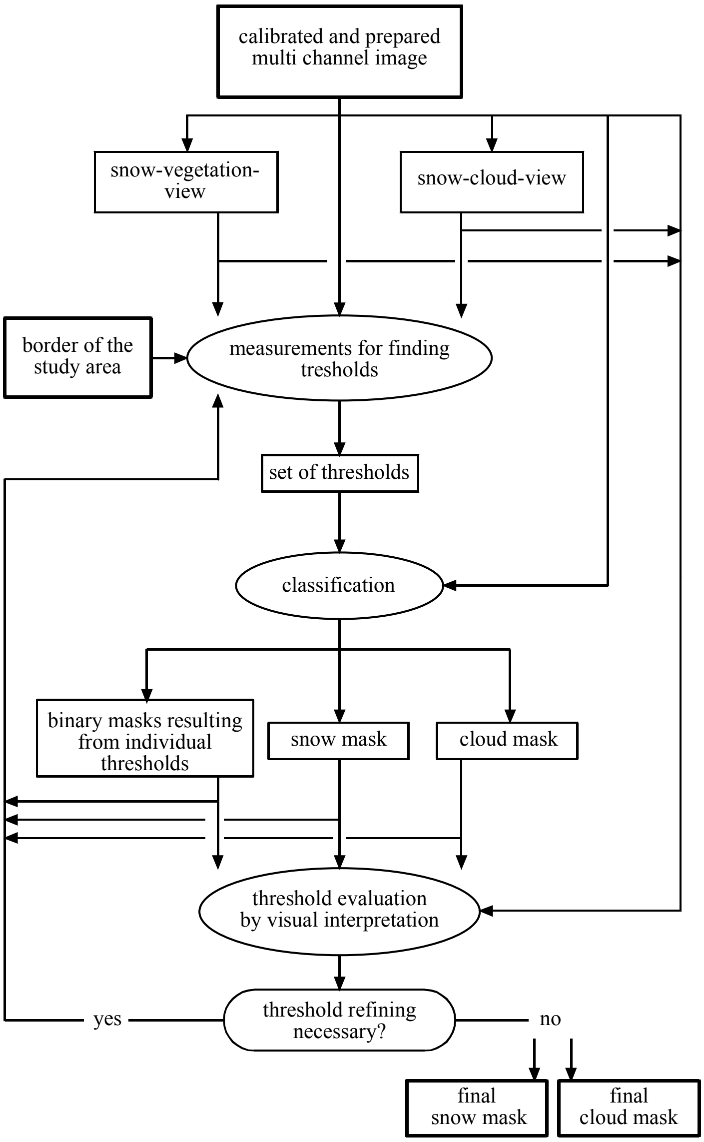


Figure 5: Threshold definition.

Using previewing tools and NOAA meta-information within each query and - in many cases after download - by visual inspections of promising data, 79 AVHRR images could be marked to fulfil both criteria. Figure 6 shows a ratio between available data in the SAA, suitable data in terms of location of the study area and, finally, useful images after a cloud check.

Because of redundant information within neighbouring winter data takes during stable weather conditions with neither snow accumulation nor depletion, 42 of the primarily evaluated images have been reselected for further processing.

While there are only minor snow variations throughout the study area during the winter period (middle of November to end of February) and the summer (middle of June to middle of September), changes can be tremendous during the main accumulation (middle of September to middle of November) and melting period (March to middle of June) even within short periods. Unfortunately, the temporal data distribution did not match very well these meteorological requirements for an ideal time series. Partly there were gaps in the most dynamic seasons. Hence, for an improved documentation of these dynamics, seven AVHRR scenes with a further off-nadir location of the study area had to be added.

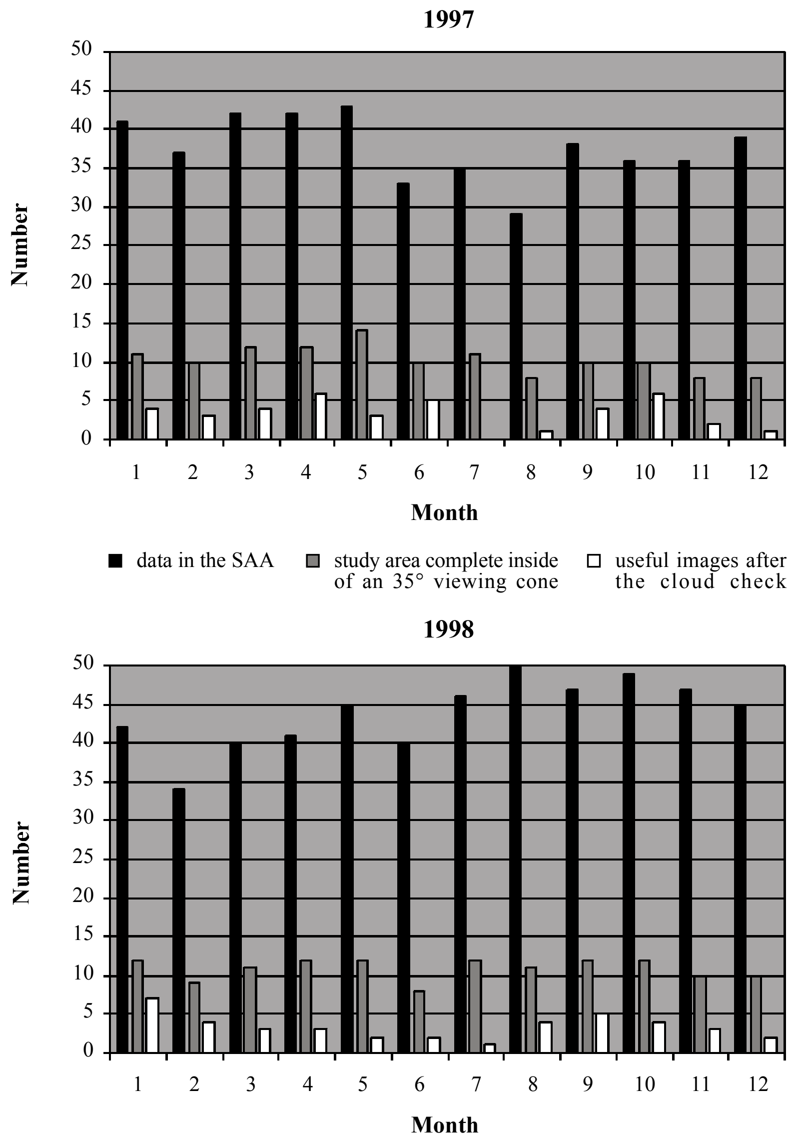


Figure 6: Data availability and suitability.

3.4 Geocoding

For a good geometric matching with other geo-data in a GIS, for the post-processing of the classification and for the derivation of space-related patterns and descriptive statements, it is necessary ***to rectify and resample the AVHRR images to a common cartographic reference system.*** A manual placing of Ground Control Points (GCPs) - a step within geocoding whole stacks of images - is very time-consuming, especially since the search of unambiguous GCPs is limited by the coarse geometric resolution. Furthermore, this approach must fail in many, namely meteorological applications, where ocean surfaces and cloud cover are subjects of interest and landmarks with defined co-ordinates are absent. Moreover, there is a strong need for efficient geocoding within all time-critical applications. By using ephemeris data of the satellites, it is possible to localise certain points within the image matrix with an accuracy of 0.05° - 0.1° (CRACKNELL, 1997), what corresponds to 4 - 10 image pixels (VOIGT ET AL., 1998). The GCP set is enclosed in Level 1b data for automated geocoding after download. To improve accuracy, it is necessary to add 'hand-navigated' GCPs to be normally placed at landmarks of known location (CAVES ET AL., 2000).

Geometrically, the achievable overall accuracy can be as good as one pixel using this hybrid approach (CAVES ET AL., 2000), a figure that is also reported for solely manually placed GCPs (VOIGT ET AL., 1998).

The wider the scan angle, the larger are the topographic displacements. If the study area is located far off-nadir, it is therefore recommended to perform an ortho-rectification with a DEM instead of simple polynomial geocoding (VOIGT ET AL., 1998). Therefore, VOIGT ET AL. (1998) have limited their data exploitation to view angles below 25°.

Our geometric processing is based on a ***hybrid approach*** with:

- coarse automated geocoding using a third-order polynomial, which has been calculated with the GCP positions coming along with the data
- an improvement through a subsequent affine transformation with parameters out of image-vector matching by distance transformation (PRECHTEL AND BRINGMANN, 1998).

The second step bypasses the difficulties of manual GCP search and placing and will be described further down. Figure 7 gives an overview on the geocoding. The resampling method has generally been 'Nearest Neighbour' in order to preserve the original data values.

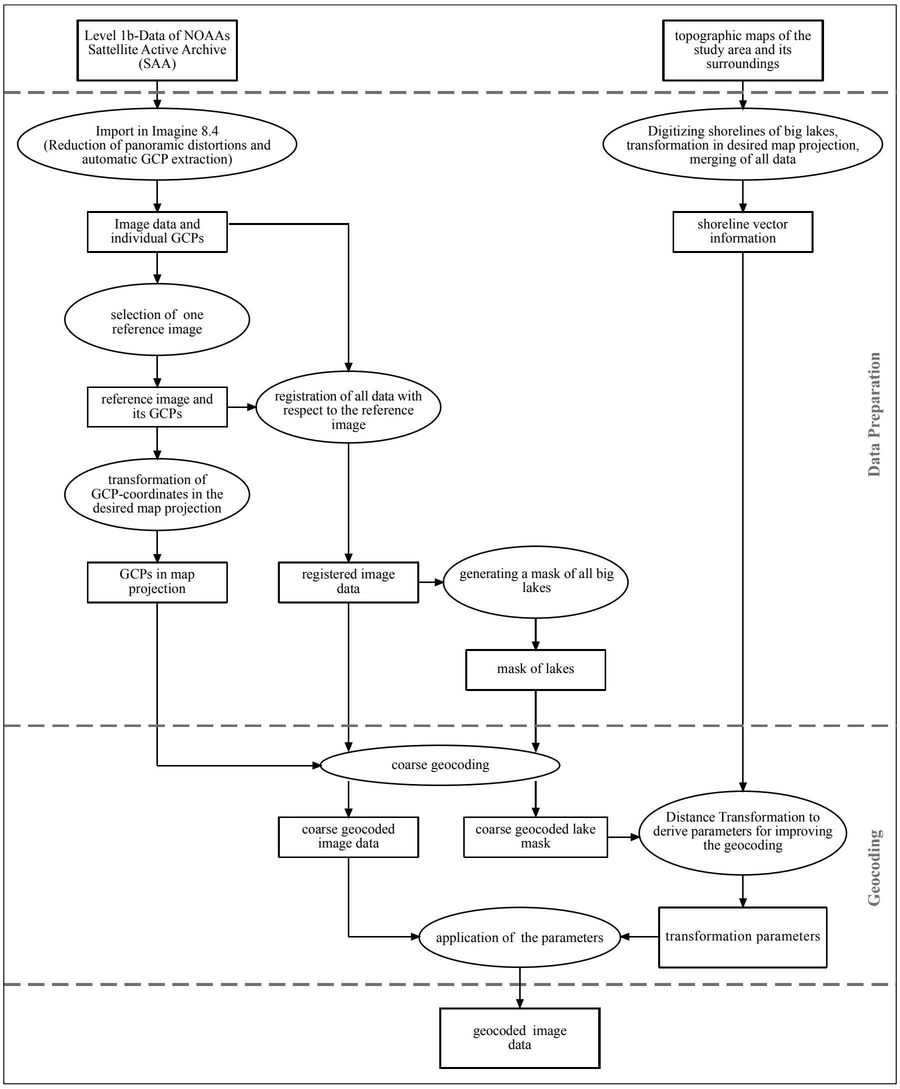


Figure 7: Geocoding of the AVHRR data.

To allow the use of ***one set of transformation parameters*** for each step only, all images got first registered to a reference or master image, which was carefully selected to meet the following requirements:

- study area and its surroundings almost cloud free,
- good recognition of all important topographic features,
- study area centred around the nadir.

For most of the images, 20 – 30 evenly distributed homologue points with the master image could be found. The RMS residuals for those points were already below one pixel when transforming with a first-order polynomial. Visual comparisons after the registration proved a very good mutual matching.

After the registration, the GCPs of the master image (geographic co-ordinates, WGS72) got transformed into the desired projection (Lambert Conformal Conic, comp. Table 1) and accordingly all images were automatically rectified with the third-order polynomial resulting from the transformed GCPs. Figure 8 (above) shows 4 subsets of the master image containing large lakes within and around the study area after the 'coarse' initial rectification step, superimposed by a map-derived vector reference.

As mentioned above, it is difficult to manually set GCPs in AVHRR imagery. Furthermore, a good geometrical fit will profit of a common reference point set, which has to be detectable in all images. This can only be assumed for shorelines of major lakes in our study area (with some restrictions for seasonal icing of some lakes). The entire set of shorelines inside has thus been considered to steer the automated derivation of geometric improvement parameters. The matching process between image and shoreline has been directed by a distance transformation (PRECHTEL AND BRINGMANN, 1998). Inputs are a binary mask of all selected water bodies of the master image and the corresponding digital reference vectors from available geographic and topographic maps.

For a given transformation rule (allowing translation, rotation and scaling), each transformation parameter is adjusted in iterations to find an optimised solution for the best match. The derived transformation parameters have then been applied to all 'coarsely' rectified images. The lower part of Figure 8 shows the reference superimposed to the subsets after improvement. The achieved overall accuracy is reliably better than two pixels.

From the size of the study area and the need to close gaps in the time series, some relevant information appeared to be situated beyond the ±25° angular threshold in a few scenes. Since no ortho-rectification could be carried out, small excess displacements to the given accuracy values can be expected in these cases.

3.5 Classification

Figure 9 at the end of this paragraph shows the classification scheme. In this type of approach, ***regional and seasonal peculiarities can and have to be considered while defining appropriate thresholds.*** The parameter tuning was strictly limited to the study area by superimposing the digital border of the Altai Republic. The multi-channel image resulting from data calibration and preparation (see chapter 3.1, Figure 4) is used either within the automated classification or as visual assistance.

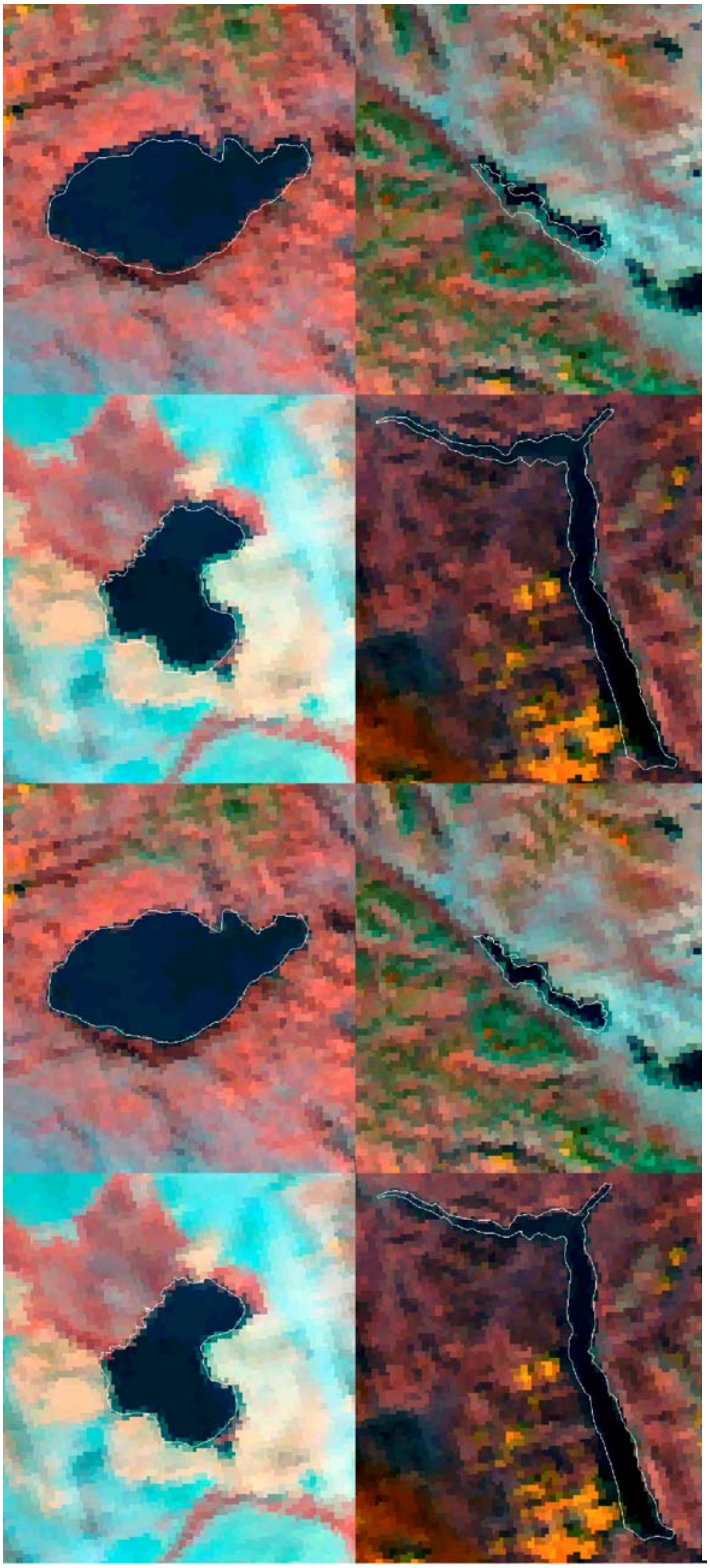


Figure 8: Geocoding results after 'coarse' rectification (above) and subsequent geometric refinement (below).

Figure 9 clarifies the classification process.

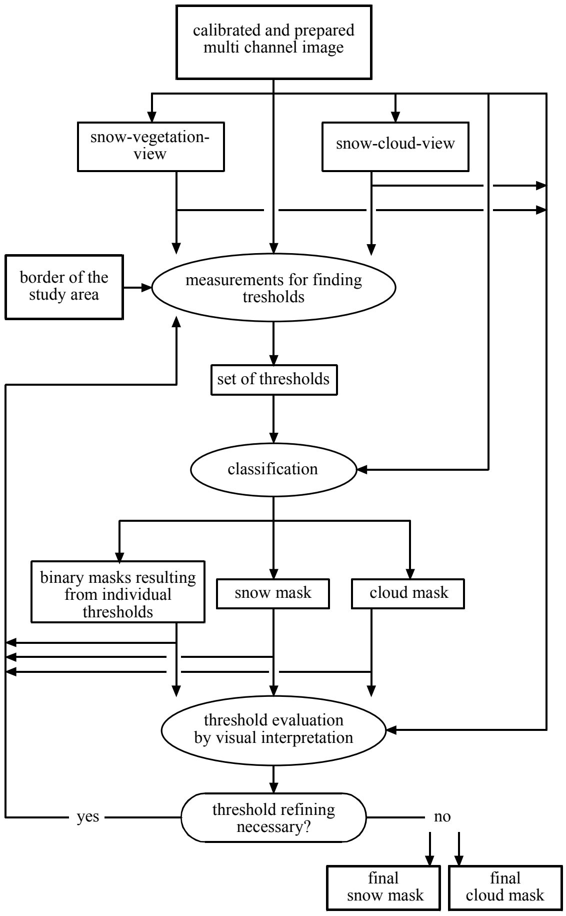


Figure 9: Threshold definition and classification.

A basic set of thresholds from measurements in our own imagery and from 'exterior' empirical findings (VOIGT ET AL., 1998) have been used for a first classification. This result has then undergone a visual evaluation and, eventually, the values had been altered until the results were in good accordance with the visual interpretations. A valuable control aid was given by two special RGB composites: The “snow-vegetation-view”, combining AVHRR-1, NDVI and reflective proportion of AVHRR-3, is useful to find thresholds for the NDVI. The “snow-cloud-view”, a combination of AVHRR-1, AVHRR-2 and the reflective proportion of AVHRR-3, helps to set reflectance limits in AVHRR-3. Besides a snow mask, a cloud mask was generated (Figure 12) to serve the post-processing of the classification.

Other studies have applied this classification scheme to areas up to 3,250 km^2. Within such a limited area, physical snow parameters are rather predictable from a more or less similar seasonal course of the snow-relevant weather elements. The Altai Republic, however, measures 93,000 km^2 and shows remarkable meteorological and climatic variations at a given time, what aggravates parameter tuning: Temperature thresholds recommended by VOIGT ET AL. (1998) have proved to be less constraining for us than other recommendations, especially since they are first in the classification hierarchy and, therefore, a weak separation feature.

After careful tuning, the final classifications appeared to be visually convincing all over the study area. Due to some inherent subjectivity, minor uncertainties definitely remain in the transition zone between 'snow' and 'no snow', and sensible changes of the critical values are leading to variations of the snow line in the range of 1 or 2 pixels. Since the main objective of the classification is the ***mapping of characteristic snow patterns over an observation period***, these differences are less critical.

So far, a proper evaluation of the classification is hindered by a poor reference. Besides a low project budget and the general problem of evaluating whole time series, the Russian project partners at Moscow, which were supposed to query and classify Russian high-resolution data to act as spot-checks, did not develop much activity. However, one snow mask of an IRS image (resolution 23.5 m) of June 17th, 1997, generated as a side product by MANNHEIM (2000) was helpful in evaluating the identical snow masks of two AVHRR-scenes dating from June 17th, 1997 and June 24th, 1997. Figure 10 shows a superimposition of the classification results for the Katoon Chain.

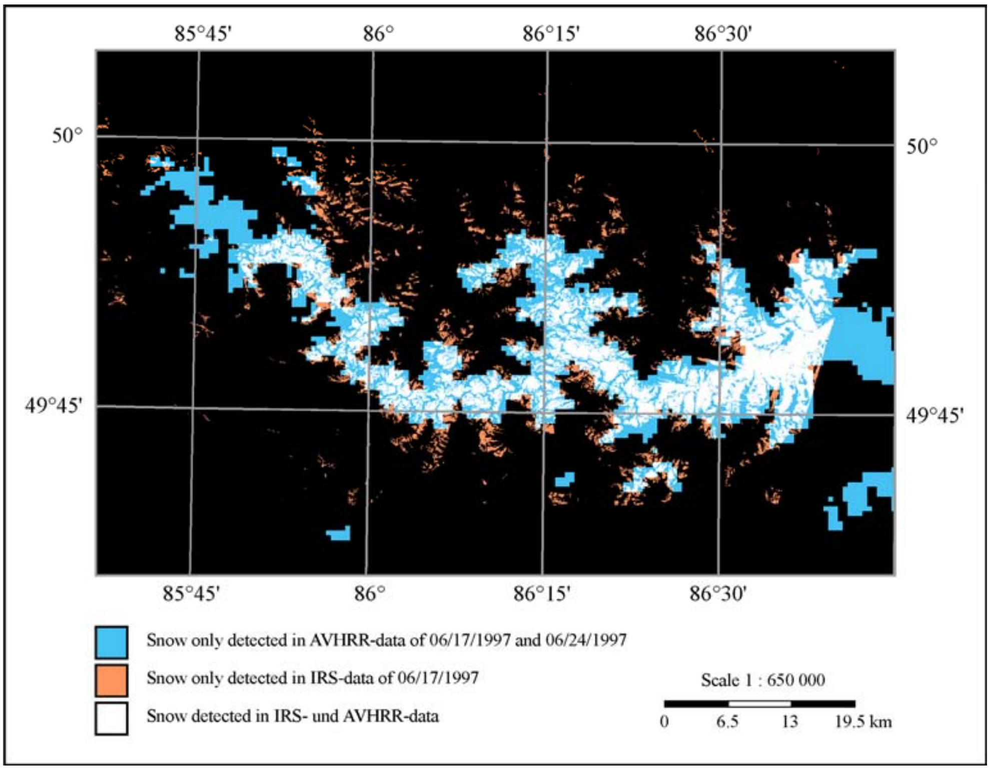


Figure 10: Comparison of classification results from IRS-1C LISS3 sensor and NOAA-14 for the Katoon-Chain.

Data gaps in the western part of the IRS snow mask result from cloud coverage. Regardless of a linear 50 times higher pixel resolution of the IRS image, there is evidence of good match of the snow lines. Even if one reference is by far not representative for the quality of all other results, it gives confidence into the method applied and the thresholds selected.

Finally, limits in the use of AVHRR (rather than limits of the algorithm of Voigt et al.,1998) shall be pointed out from our experience:

- detection of snow in densely forested areas (in particular coniferous forest)
- detection of snow in shadows
- separation of snow and clouds under very cold surface temperatures (not untypical at all for the winters in a high-continental setting)

Forested and shadowed areas form the dominating problem. Low reflection in AVHRR-1 causes pixels to fail the albedo test. Figure 11 shows a superimposition of the classification results and the forest cover for Katoon-Chain and Uimon-Steppe. At wintertime, the land is mostly snow-covered, what is not reflected by the classification, where the distribution pattern looks almost identical to the one of March 1st,1997.

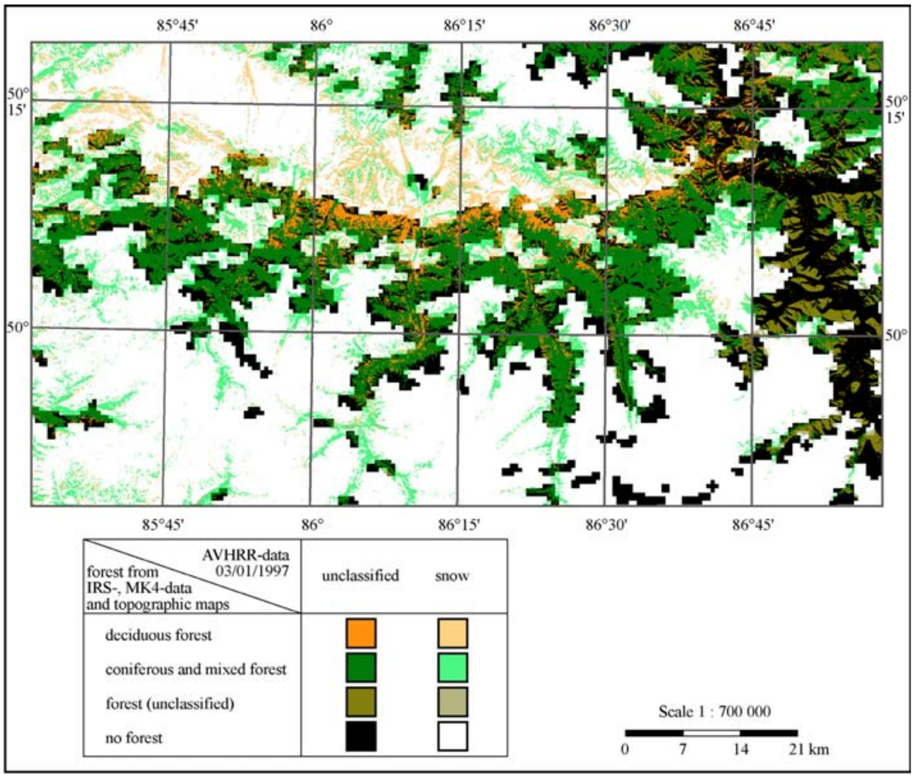


Figure 11: Comparison between the patterns of a high winter snow classification from AVHRR and a high-resolution forest layer. Scale reduced to 1:1,000,000.

The hard separation problems between clouds and snow for the extremely cold high-winter condition (with fortunately little precipitation) could partly be solved by using the previous or next cloud-free images, assuming, that, if ever, locally only snow depth might have changed without much influence on the generally stable horizontal snow distribution.

3.6 Post-processing of the classification results – extrapolation under clouds

Advancing the GIS integration and map generation, the set of classifications had to undergo some additional processing such as:

- rejection of most likely classification errors for snow (based on statistics of snow distribution in comparison to DEM elevation)
- reassignment of isolated pixels to 'snow', 'cloud' or 'no snow' based on neighbouring 'valid' assignments
- extrapolation into classification gaps under cloud cover.

Most challenging is the extrapolation, since the method should accommodate to a specific regional situation, should require few additional data and easily be implemented. Existing approaches are either not satisfactory because of simplicity (WILHELM, 1975) or require extensive additional information not available (EHRLER, 1998). Our approaches incorporate strategies of EHRLER (1998), but had to be simplified in terms of supplementary data and to be modified in terms of the extrapolation algorithm. The only data supplement was the open-source DEM 'GTOPO30' with a cell resolution similar to AVHRR data. The basic idea, which has been adapted from EHRLER, was the segmentation into Snow Classification Units (SCUs), accounting for the influence of elevation, slope and aspect on snow patterns. By defining 5 aspect classes (North, West, South, East, flat) and 3 inclination classes (<8°; 8°-< 19°, ≥ 19°), all DEM ground cells were grouped. Together with the absolute elevation these SCUs could then be used for a stratified extrapolation.

As mentioned, the approach had to reflect regional differences or, in other words, the distance-dependent probability, that snow patterns would be analogue in distribution or not. A global statistical examination and assignment of 'cloud pixels' to 'snow' using SCUs would have been inappropriate. Two other methods were tested and proved to deliver good results.

The first approach, called Moving Window (MW), extrapolates snow under clouds by comparing only SCUs inside a certain distance from the pixel of interest. A predefined window is moving and SCU-wise examined pixels are assigned to snow, if snow pixels inside the window are found with an elevation below the cloud pixel. The MV appeared to be suitable for small single clouds or open cloud clusters. Congested clouds and cloud banks cause the MV to fail due to insufficient reference information in the window. Expanding the window means offending the demand for a region-specific treatment.

The second method is based on a Delaunay Triangulation (DT; KRAUSS, 2000) of snow line elevations, also stratified according to SCUs. Pixels of interest are assigned SCU-wise to be snow when their elevation is below the surface created by the DT. This approach works well under larger cloud clusters and is still reflecting local deviations (what can be checked through the triangular mesh size). It will fail for a scattered snow distribution and, thus, a vague snow line definition.

For an evaluation, snow masks of two AVHRR images with extended snow and very low cloud cover were numerically corrupted by a large (fictive) cloud mask taken from another AVHRR-image. Figure 12 represents such a degraded data set and the extrapolation results after applying MV and DT. For the MV approach, the results are varying with the size of the window. While it was possible to assign almost all corrupted snow pixels after expanding the window, the occurrence of extrapolation errors increased, too. Using DT was leading to more stable results with, globally calculated, more than 75% of successful recovery and small amounts of error.

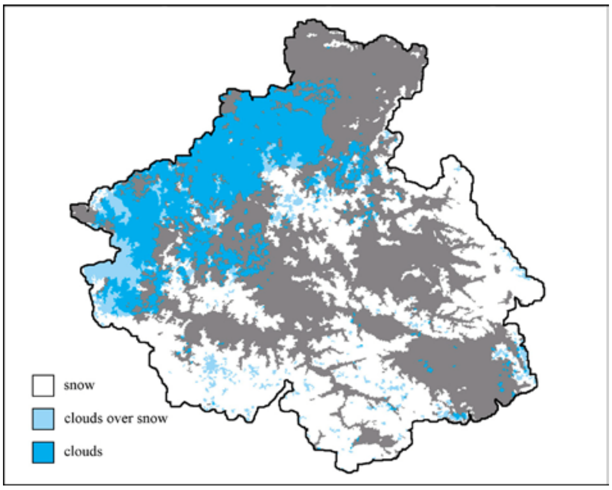
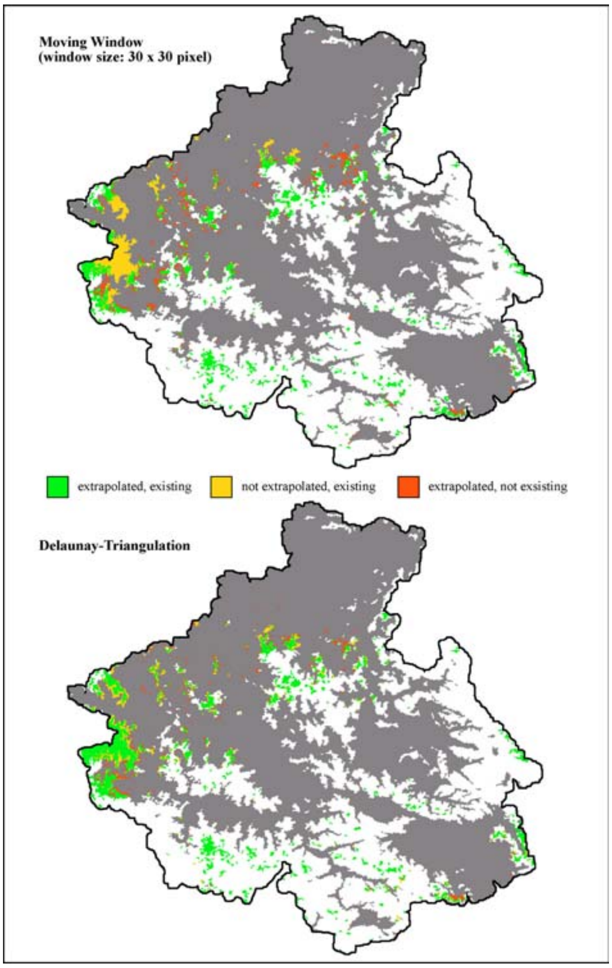


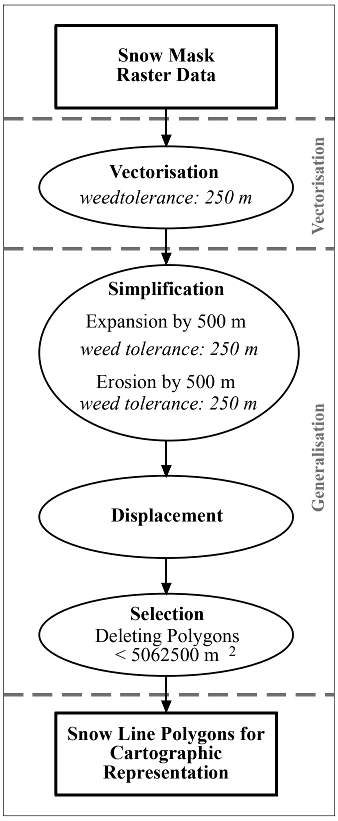
Figure 12: The synthetic configuration for the extrapolation tests.



In the study, both approaches have been applied depending on the snow and cloud situation of each individual data set.

Due to the lack of reliable information on the basic vegetation classes for the Altai Republic (which has so far been generated for the 'inner study area' of the Katoon Range, only), it was impossible to improve the snow masks for areas, where the classification might have failed under dense forest. Such a refinement is, however, envisaged in the near future. Further under-estimations caused by cast shadows were not subject of post-processing since it would have required an accurate individual illumination simulation for each individual scene.

Figure 13: Comparison of the extra-polation results with 'MV' and 'DT' approach.



3.6 Cartographic presentation

The final raster snow masks had subsequently to be converted into vector data for a more efficient GIS integration and for an improved cartographic design potential. Within this step, a moderate generalisation could also be included as represented by Figure 14.

The selection criterion for the generalisation is based on minimum dimensions of area elements with colour filling. As specified by HAKE AND GRÜNREICH (1994), the area limit is 1 mm^2 and has been expanded to 1.5 x 1.5 mm^2 in our case to reliably ensure a good readability. Applying it to the final map scale of 1 : 1,500,000, this equals to about 5 km^2 in reality, what is still pretty fine for a small-scale map.

Figure 14: Processing steps from classified raster snow mask to GIS snow coverage.

Furthermore, the final snow distribution maps had to meet the following requirements in terms of ***cartographic design:***

- fitness for use and plausibility for all co-operation partners
- efficient, appealing and clear appearance of the snow distributions over the observation period
- a clear presentation of relief information
- introduction of important elements of orientation.

All text in the map had to be shown in English, what was implying a conversion of geographic names from the Cyrillic alphabet. General geographic terms like 'lake' or 'plateau' could be translated. Names are problematic. After evaluating advantages and disadvantages of transcription and transliteration, the latter was chosen. The Cyrillic letter “u” appears in many names and strongly influences the English pronunciation. Thus, to improve the phonetic likeliness, a transcription was done in advance for this letter only.

Other requirements could neither be met easily. The complex snow patterns did not allow a joint visualisation of many stages in one sheet. This is the more true, as it was desired to add quite some information on relief, drainage and settlements. Some additional map features shall be named: The background of all maps was uniformly designed and directly related to the maximum snow variation for the whole observation period. This allows to compare the specific snow stages with the extreme ones and also reduces the number of individual map sheets needed as a result of the 'stability' of the winter maximum. The minimum snow situation has been derived from an image dating from August, 1998, the maximum stage was compiled from six winter images, all taken in January and February. A graphical merge of the extremes was done by displaying the maximum accumulation in blue and the maximum depletion in red. A light blue background is indicating areas where snow could never be detected despite of a high probability of being present at wintertime. The colour-coded maximum snow variation has then been merged with an analytic hill shading to add a relief impression, which is further supported by selected spot elevations.

Tests have shown that map users are not able to get a realistic impression of the distributions, when snow-covered and snow-free areas are visually divided by boundary lines only (without fillings). But through introducing line hatches with an opposite orientation, two stages could clearly be presented without suppressing much of the background information. Of further interest was the colour code of the area fillings. On one hand, it should enable a better discrimination between the two stages jointly mapped in a sheet, on the other hand, colour should indicate the transition from winter to summer or vice versa. 10 colours have been selected to associate the seasonal transition and to contrast to the background colour scheme. This was working nicely in the legend, but we found it hard to distinguish between the two stages in the map face, since the hatch colours were obviously quite close in the colour space. Thus, a static colour pair has finally been chosen, with the 'warm' colour always representing the date closer to the summer situation (Figure 15).

The restriction to two stages in one map made a general map legend a must. It has been designed to give an overview on all dates mapped along with an index pointing to the relevant dates of each individual sheet. Figure 15 shows the legend.

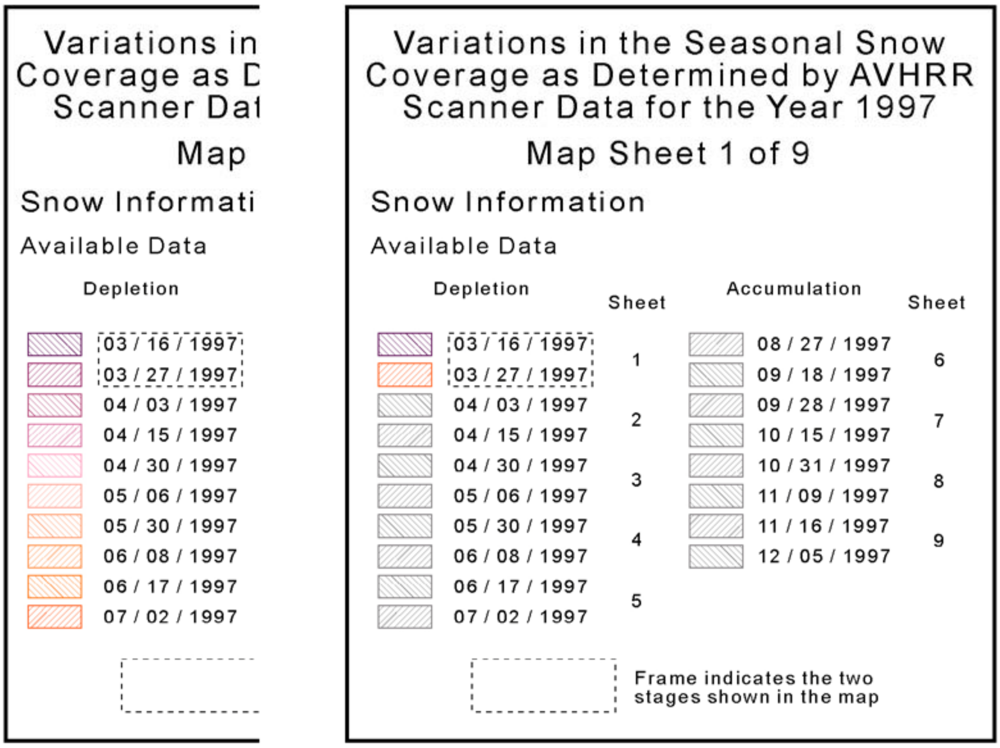


Figure 15: The general legend in the initial form (left) and the final form (right).

Figure 16 represents a subset of one final snow map.

4. Conclusion and outlook

The main objective of the present study was to evaluate AVHRR data for detecting and mapping the seasonal variation of snow cover with the highest observation frequency sensible (in terms of the real-world dynamics) and possible (in terms of available data). The study area is covering 93,000 km^2 of mountainous terrain in the south of Siberia with highly variable relief and climate conditions. The analysis is based on NOAA-14 data for the years 1997 and 1998. Extensive investigations in the SAA of NOAA resulted in a huge number of data entries. Restrictions, mainly due to scan angle and cloud coverage, reduced this number tremendously and have partly urged us to use some less appropriate scenes for the period with high snow dynamics. Several corrections and calibrations were advancing the data analysis. Geocoding of the AVHRR images was achieved by a multi-step approach. For efficiency, an initial step was a registration of all imagery to a master image. A second step performed a polynomial transformation based on AVHRR header information, a third a geometric refinement using image-vector matching steered by a distance transformation.

A fully automated classification was not feasible due to highly variable radiometric characteristics, a lack of extensive reference data for tuning and evaluation and other restrictions published by other authors. Therefore, the choice was a hierarchical pixel-based threshold method developed at Bern University. Defining individual thresholds was the crucial point since major climatic variations within the large area have been expected and found. Nevertheless, it was possible to obtain reliable snow patterns. Data-inherent deficiencies exist for densely forested areas and shadow zones. Closing of classification gaps under clouds was achieved by using DEM information and two different extrapolation techniques.

A cartographic presentation of the results was realised by a map series. Each sheet contains two consecutive snow stages. Inevitably, the user has to go through the series, to capture the seasonal dynamics. A further more generalising analysis of the patterns is a pending GIS task, which is envisaged for the near future.

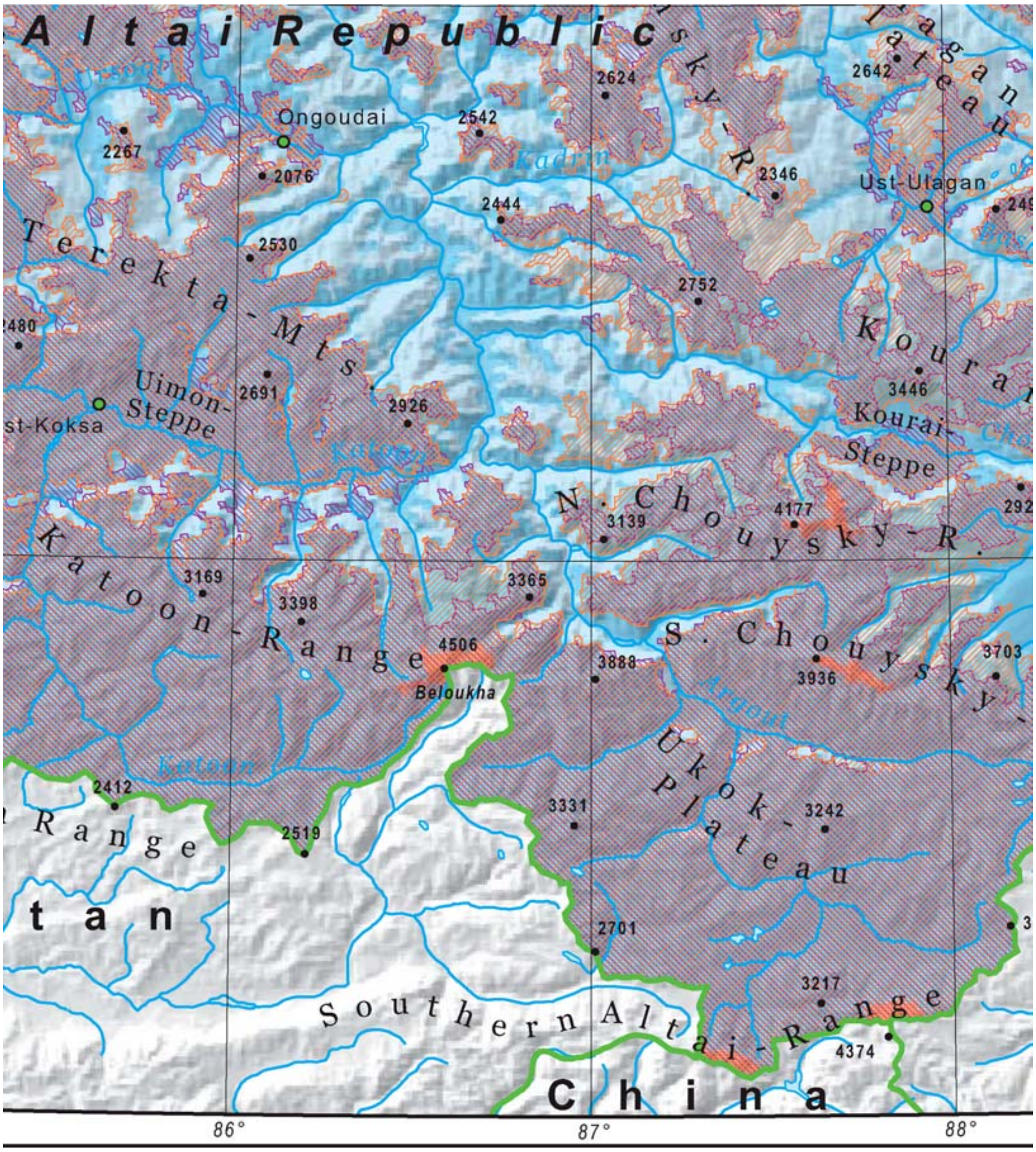


Figure 16: Small section of the final snow map.

Small positional deviations of the snow line between two consecutive stages (in the range of 1-2 pixels) can be realistic, but also be artefacts. Reasons for the latter can be:

- different illumination affecting the classification
- different primary data resolution from the varying view angle
- matching inaccuracies and
- minor uncertainties in the threshold settings.

The results do well reflect the general seasonal snow variation and regional peculiarities. Moreover, a concise document for a large area has been created, which will probably be more reliable than an analysis based on the few meteo-stations centred in valley locations and hardly representative for high elevations. Nevertheless, the results still have to be cross-checked with some high-resolution material. Moreover, it would be desirable to increase the observation frequency for the main accumulation and melting period. Both requirements could theoretically be matched by adding Russian meteorological and earth observation imagery. Such a densification and evaluation with high resolution would also allow to better interact with a detailed relief and vegetation model. Exactly this is planned for the Katoon Range, where the 'ALTAI100-GIS' already by now delivers these most essential modules.

References

ALLEN, R.C., DURKEE, P.A. & WASH, C. H. (1990): Snow / Cloud Discrimination with Multispectral Satellite Measurements. Journal of Applied Meteorology, Vol. 29, pp. 994 – 1004.

ASTE, C. (1993): Habitatqualität für Braunbären in Österreich (Habitat Quality for Brown Bears in Austria). Unpubl. Diploma Theses at Universität für Bodenkultur, Tutor Prof. Gossow, Vienna, 95 p.

BUCHROITHNER, M.F., PRECHTEL, N. & CH. HESSING (1997): High mountain game habitat assessment using remote sensing. - In: Bax, G.(ed.): Proc. of the 4th Intern. Symp. on High Mountain Remote Sensing - The University of Karlstad Research Report 97:3 (Natural Sciences/Technology), Karlstad, pp. 61-69.

BUTVILOVSKIY, V.V. (1993): Paleogeografia poslednewo oledenenya i golocenia Altaya: sobuytino-katastroficheskaya model (Paleo-Geography of the Altai in the Last Ice-age and Holocene). Tomsk University Press, Tomsk, 251 pp.

CAVES, R.G., TURPIN, O.C., CLARK, C.D., FERGUSON, R.I., QUEGAN, S. & JOHANSSON, B. (2000): The Use of Earth Observation for Monitoring Snowmelt Runoff from Non-Alpine Basins. In: Casanova (ed.): Remote Sensing in the 21st Century: Economic and Environmental Applications, Balkema, Rotterdam, pp. 183 – 190.

CICHOWSKI, D. B. (1993): Seasonal movements, habitat use and winter feeding ecology of woodland caribou in west-central British Columbia. Land management report, No. 79, Research Branch, Ministry of Forests of British Columbia, 76 p.

CRACKNELL, A. P. (1997): The Advanced Very High Resolution Radiometer. Taylor & Francis Ltd, London.

DERRIEN, M., FARKI, B., HARANG, L., LEGLEAU, H., NOYALET, A., POCHIC, D. & SAIROUNI, A. (1993): Automatic Cloud Detection Applied to NOAA-11 / AVHRR Imagery. Remote Sensing of Environment, Vol. 46, pp. 246 – 267.

EHRLER, C. (1998): Klimaänderung und alpine Schneedecke - Auswirkungen auf das Abflussregime am Beispiel des Einzugsgebiets „Rhein-Felsberg“. (Climate change and alpine snow cover – Influence on the discharge using the example of the Rhein-Felsberg catchment). Projektschlußbericht des nationales Forschungsprogrammes „Klimaänderung und Naturkatastrophen“, NFP 31. vdf, Hochschulverlag AG an der ETH Zürich.

GESELL, G. (1989): An Algorithm for Snow and Ice Detection Using AVHRR Data – An Extension to the APOLLO Software Package. International Journal of Remote Sensing, Vol. 10, No.4, pp 897-905.

HAKE, G. & GRÜNREICH, D. (1994): Kartographie. Walter de Gruyter, Berlin/New York.

HALL, D.K. & MARTINEC, J. (1985): Remote Sensing of Ice and Snow. Chapman and Hall Ltd.

HARTMAN, R.K., ROST, A.A. & D.M. ANDERSON (1996): Operational processing of multi-source snow data. 3rd International Conference/Workshop on Integrating GIS and Environmental Modeling, Santa Fe, NM, January 21st – 25th, 1996, 10 p.

HENDERSON-SELLERS, A. (1984): Satellite Sensing of a Cloudy Atmosphere: Observing the Third Planet. Taylor & Francis, London and Philadelphia.

HINDELANG, M. (2001): Winter Ecology. Michigan Technological University¹s Winter Ecology Institute. http://www.ed.mtu.edu/esmis/winter/ecology.html.

HÖPPNER, E. (2001): Untersuchungen zur Kartierung der saisonalen Schneebedeckung im Russischen Altai mittels meteorologischer Fernerkundungsdaten (Investigations on the mapping of seasonal snow cover of the Russian Altai using meteorological remote sensing data). Unpubl. Diploma Theses at Dresden Univ. of Techn., Tutors Prof. Buchroithner & Dr. Prechtel. Dresden, 109 p.

KRAUSS, K. (2000): Photogrammetrie 3 – Topographische Informationssysteme (Topographic Information Systems). Dümmler-Verlag.

KAISER, U. & B. KÖNIG (1998): Das Altai-Gebirge - Untersuchungen zu Naturschutz- und Tourismuseignung (Schwerpunkt Rayon Ust-Koksa) (The Altai Mountains - Study of conservation and tourism potential). Unpubl. Diploma Thesis at Dresden Univ. of Techn., Tutor Prof. Kowalke. Dresden, 109 p.

MALONE, S., CERRETANI, J. & S. KELLING (2000): Birds and snow. - Birdscope, Vol. 14, No. 3, pp. 6-7.

MANNHEIM, S. (2001): Kartierung der aktuellen Waldbedeckung im zentralen Altai (Südsibierien) mittels Fernerkundung und Feldaufnahmen. (Mapping of the actual forest cover in the Central Altai using remote sensing and ground truth). Diploma thesis at Dresden University, Tutors Tutors Prof. Buchroithner & Dr. Prechtel. Dresden, 129 p.

MAXSON, R.W. (1992): Comparison of Areal Extent of Snow as Determined by AVHRR and SSM/I Satellite Imagery. Thesis (AD-A258 054), Naval Postgraduate School, Monterey, California.

NOAA (2000): NOAA Polar Orbiter Data User's Guide: http://www2.ncdc.noaa.gov:80/docs/podug/index.htm

PRECHTEL, N. (1998): Concepts and preliminary results of environmental mapping in the Katoon-Chain of the Altai-Mountains (Siberia). Proceedings of Workshop Hochgebirgskartographie der DGfK (German Society of Cartography), Silvretta, February ´ 98 = Wiener Schriften zur Geographie und Kartographie, Vol. 11, Vienna, pp. 130-144.

PRECHTEL, N. & BRINGMANN, O. (1998): Near-Real-Time Road Extraction from Satellite Images Using Vector Reference Data. ISPRS-Proceedings, Volume XXXII, Part 2, Commission II: Data Integration: Systems and Techniques, pp. 229 – 234.

PRECHTEL N. & M.F. BUCHROITHNER (2001): The contribution of remote sensing to alpine tourism in protected landscapes. The example of the Altai Mountains. - Proceedings of the Working Group on High-Mountain Remote Sensing Cartography. in print.

PRECHTEL, N. (2002): Selected problems and solutions for drainage modelling and handling in a GIS. – Internationales Korrespondez-Seminar – Diskussionsbeiträge zur Kartosemiotik und zur Theorie der Kartographie 4/2001, pp. 29-38.

RAO, C.R.N. & CHEN, J. (1996): Post-Launch Calibration of the Visible and Near-Infrared Channels of the Advanced Very High Resolution Radiometer on the NOAA-14 Spacecraft. International Journal of Remote Sensing, Vol. 17, pp. 2743 – 2747.

RAO, C.R.N. AND CHEN, J. (1998): Revised Post-Launch Calibration of Channels 1 and 2 of the Advanced Very High Resolution Radiometer on Board of the NOAA-14 Spacecraft. http://psbsgi1.nesdis.noaa.gov:8080/EBB/ml/niccal1.html

SAA - SATELLITE ACTIVE ARCHIVE: http://www.saa.noaa.gov

SAUNDERS, R.W. & KRIEBEL, K.T. (1988): An Improved Method for Detecting Clear Sky and Cloudy Radiances from AVHRR Data. International Journal of Remote Sensing, Vol. 9, No. 1, pp. 123 – 150.

D'SOUZA, G., BELWARD, A.S. & MALINGREAU, J-P. (1996): Advances in the Use of NOAA AVHRR Data for Land Applications. Euro Courses, Remote Sensing, Volume 5: Advances in the Use of NOAA AVHRR Data for Land Applications, pp. 21 – 47.

SIMPSON, J.J., STITT, J.R. & SIENKO, M. (1998): Improved Estimates of the Areal Extent of Snow Cover from AVHRR Data. Journal of Hydrology 204, pp. 1 – 23.

STARDOM, R.P. (1977): Winter ecology of Woodland Caribou, and some aspects of winter ecology of Moose and Whitetail Deer in southeastern Manitoba. M.Sc. Thesis, Univ. of Manitoba, 157 p.

STEFANOVIC, P. & G. WIERSEMA (1985): Insolation from digital elevation models for mountain habitat evaluation. ITC-Journal 1985/3, pp. 177-186.

VARIOUS AUTHORS (1996): Krasnaya kniga respubliki altai (The red book of the Altai Republic). Russian Academy of Science, Siberian Branch, Novosibirsk, 256 p.

VOIGT, S. (1998): HYDALP – Hydrology of Alpine and High Latitude Basins. Internal Report RI333: WP 333 – Documentation of MROI Methods for Snow Cover Mapping, Bern University.

VOIGT, S., KOCH, M. & BAUMGARTNER, M.F. (1999): A Multichannel Threshold Technique for NOAA AVHRR Data to Monitor the Extent of Snow Cover in the Swiss Alps. Interactions Between the Cryosphere and Greenhouse. Procceedings of IUGG 99 Symposium HS2, Birmingham, IAHS Publications, No. 256, pp. 35 – 43.

WILHELM, F. (1975): Schnee- und Gletscherkunde (Snow and Glacier Science). Walter de Gryter, Berlin/New York.

YAMANOUCHI, T. & KAWAGUCHI, S. (1992): Cloud Distribution in the Antarctic from AVHRR Data and Radiation Measurements at the Surface. International Journal of Remote Sensing, Vol. 13, pp. 111 – 127.